Microvascular Materials for Mass and Energy Transport

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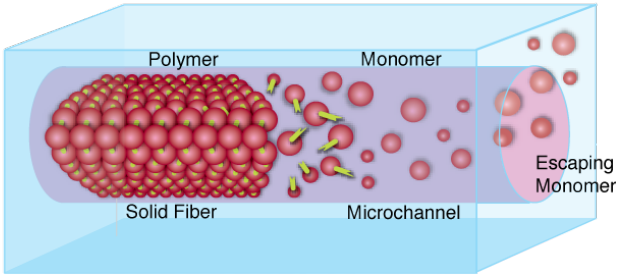
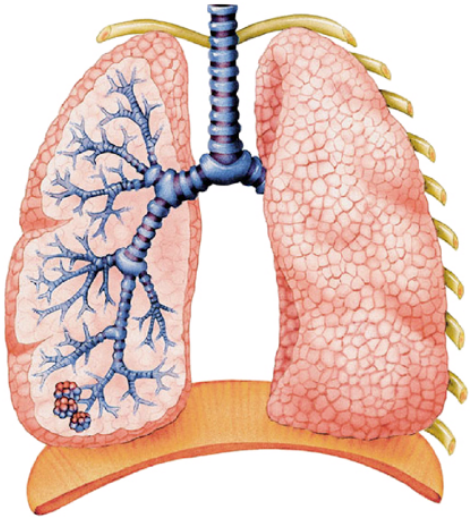
Micro-Vascular Exchange Units : Bio-Inspired Energy & Mass Transfer

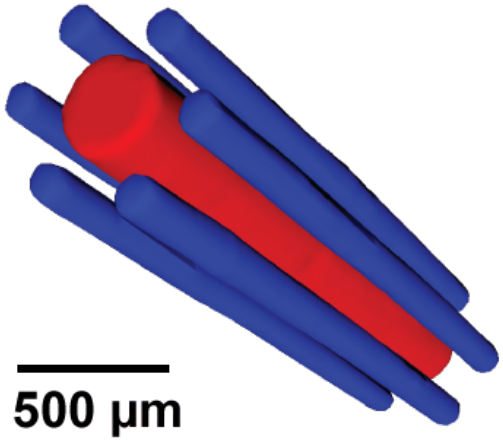
VaSC – Vaporization of a Sacrificial Component



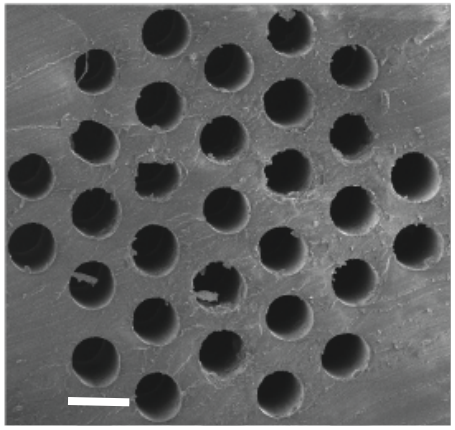
Our Motivation



Exchange Unit

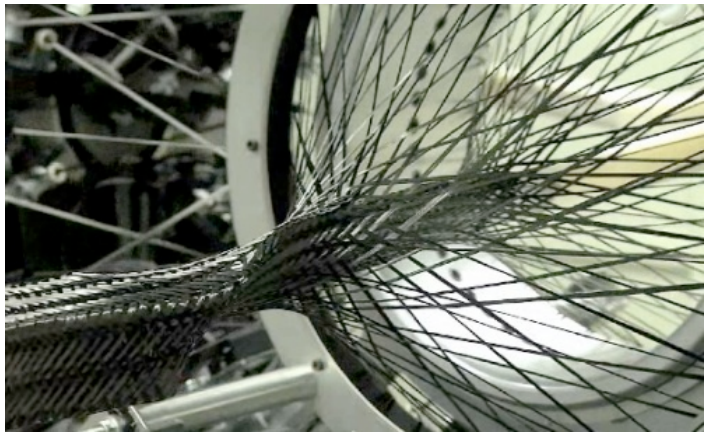


Optimization

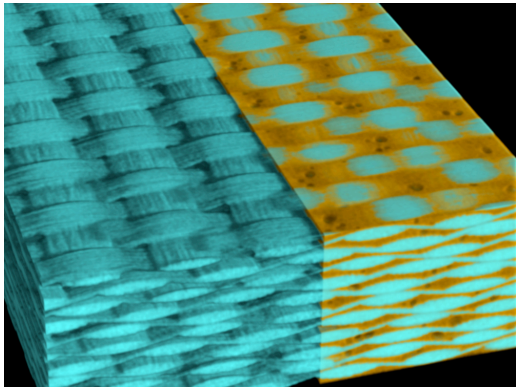


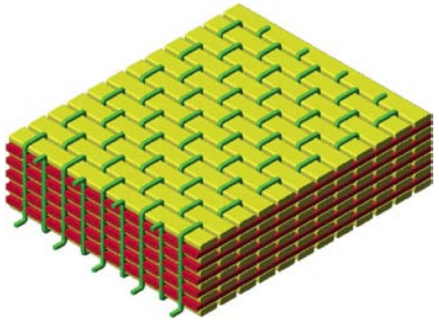
500 um

Fiber Reinforced Composites



Fiber Composite, Stronger, Lighter



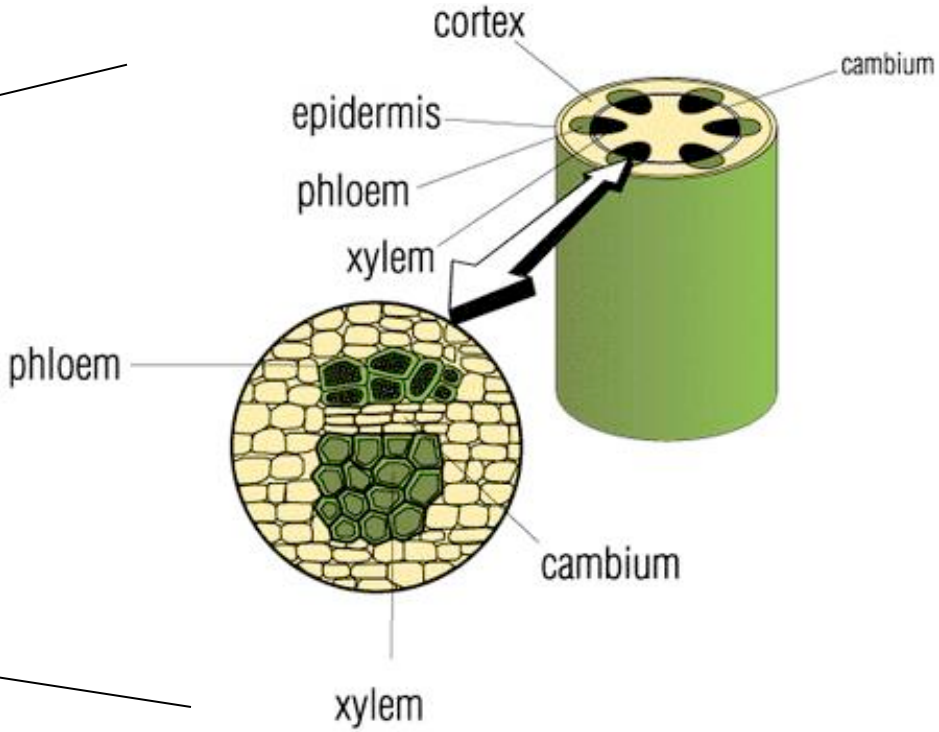


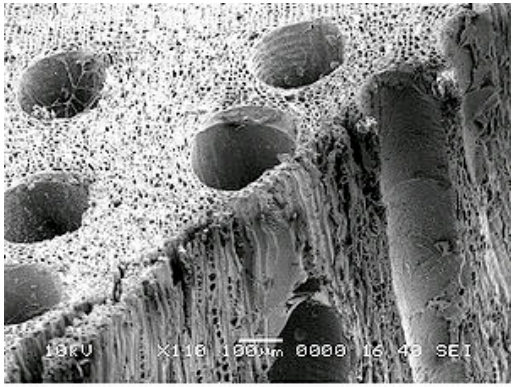
Interwoven fibers provide strength

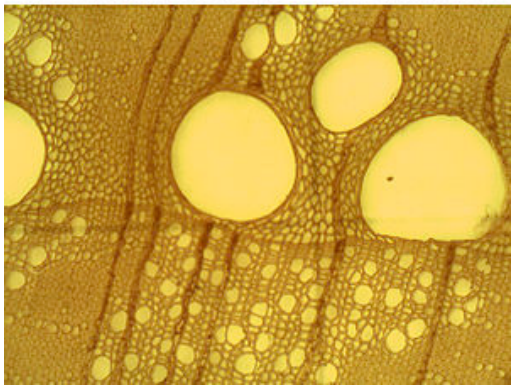
50% Composite, 30% Lighter

Trees: Nature's Composites

Pacific Yew Tree



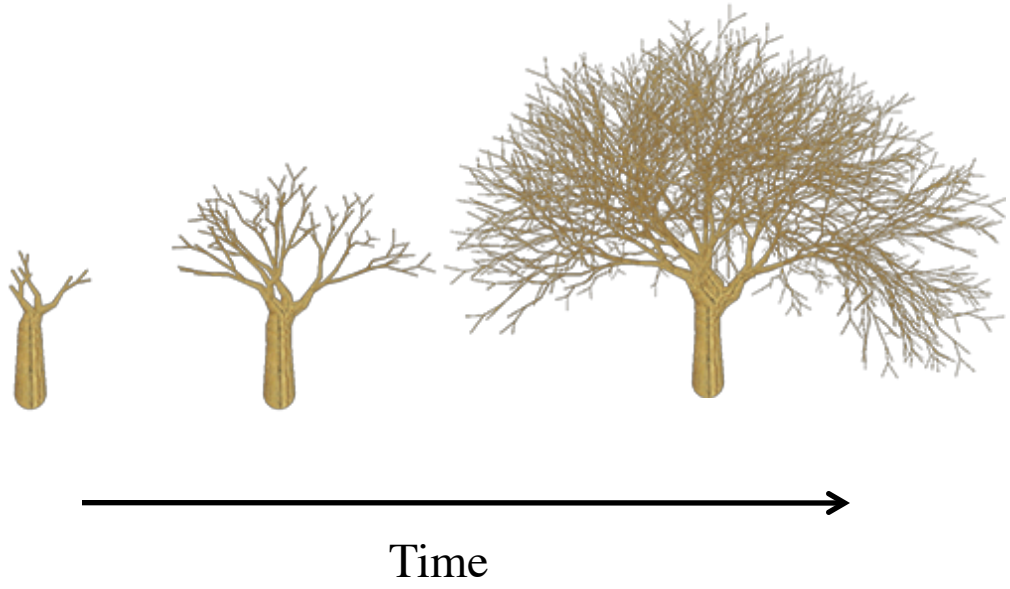




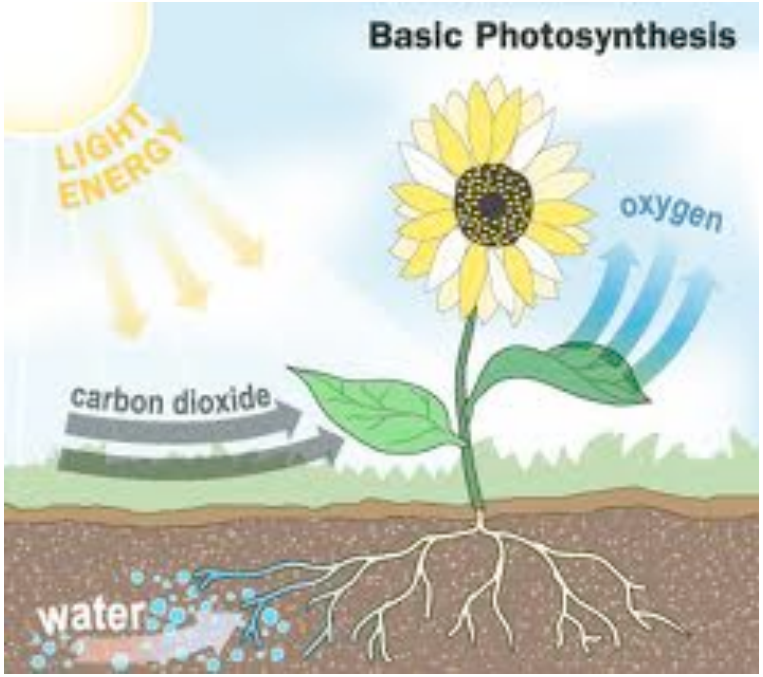
Vasculature Creates Living Materials

E/M Transport + Regional Chemistry = Growth, Homeostasis, Communication

Growth

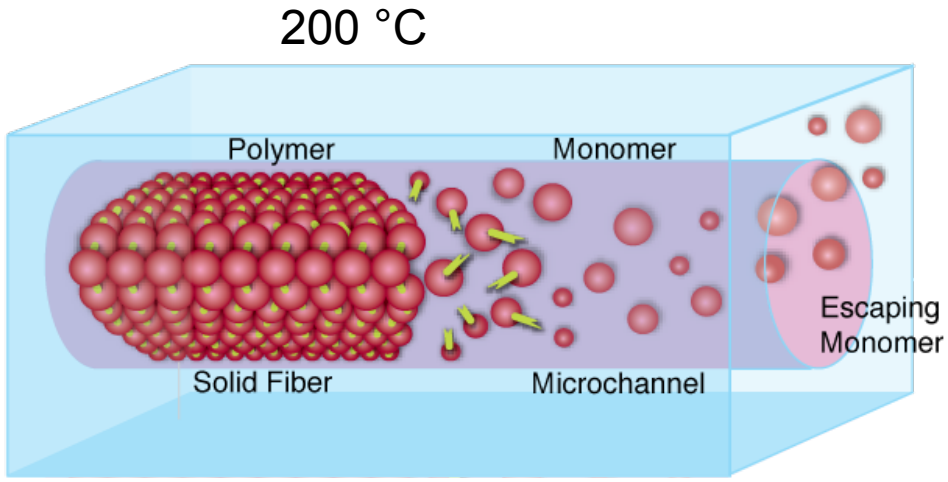


Reactivity



VaSC – Vaporization of a Sacrificial Component

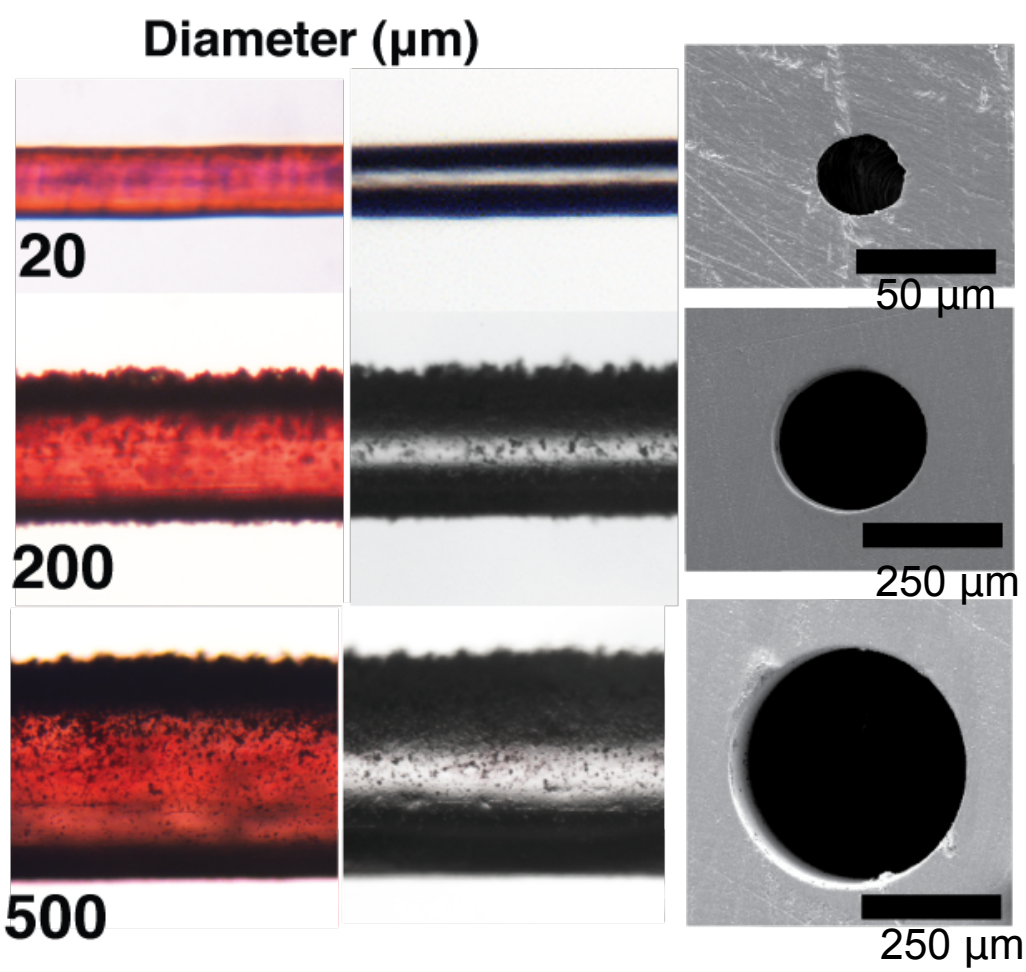
Gas

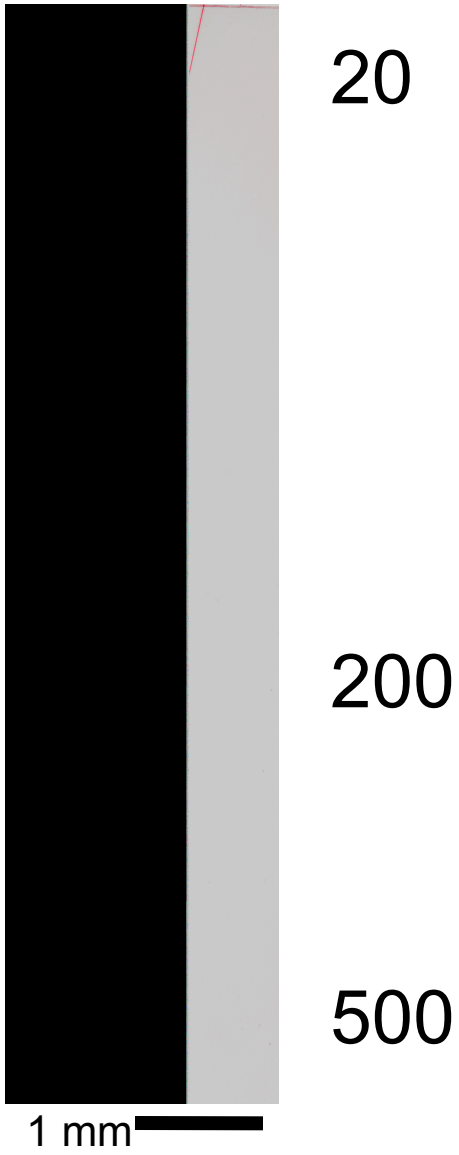


Empty Channel

Esser-Kahn, A. P.; Thakre, P. R.; Dong, H.; Patrick, J. F.; Vlasko-Vlasov, V. K.; Sottos, N. R.; Moore, J. S.; White, S. R. *Advanced Materials* ***2011, 23, 3654–3658***

Size Range & Connection of Fibers

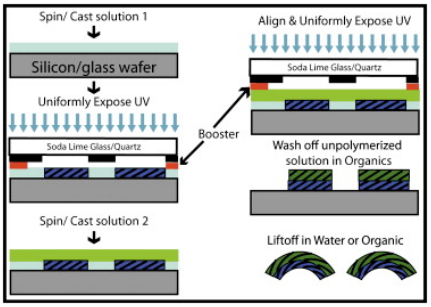


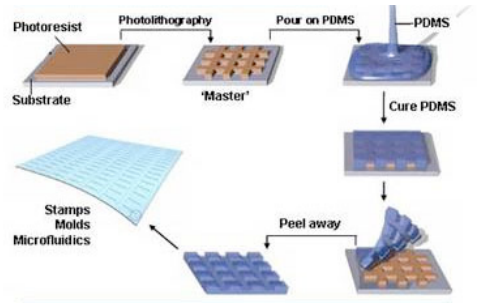


- **Varying diameters of range 20-500 µm**

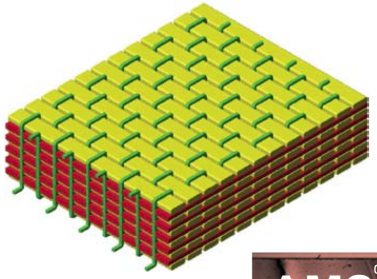
Different Micro-Fabrication Methods for Materials: Hamburger to Celery

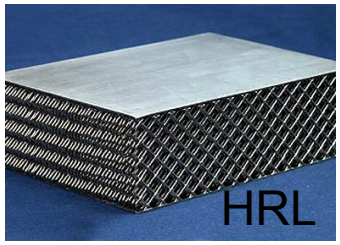
Lithography

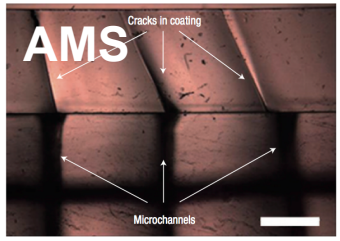


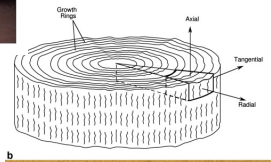


3D Techniques



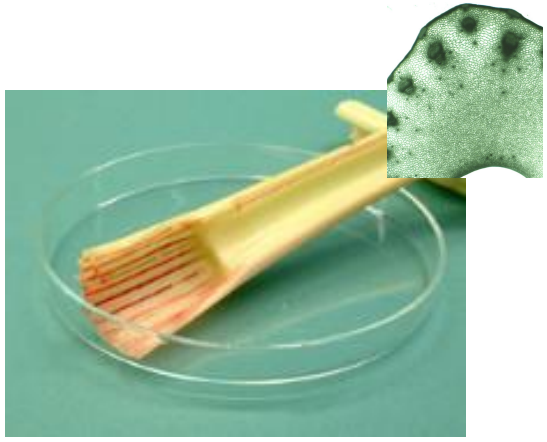


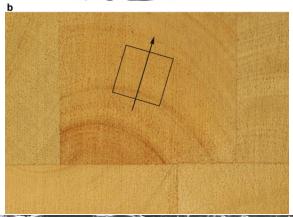


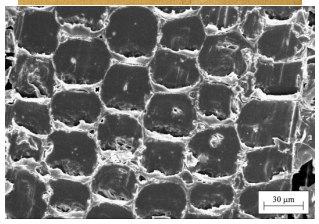


Big Mac Assembly

Celery Assembly

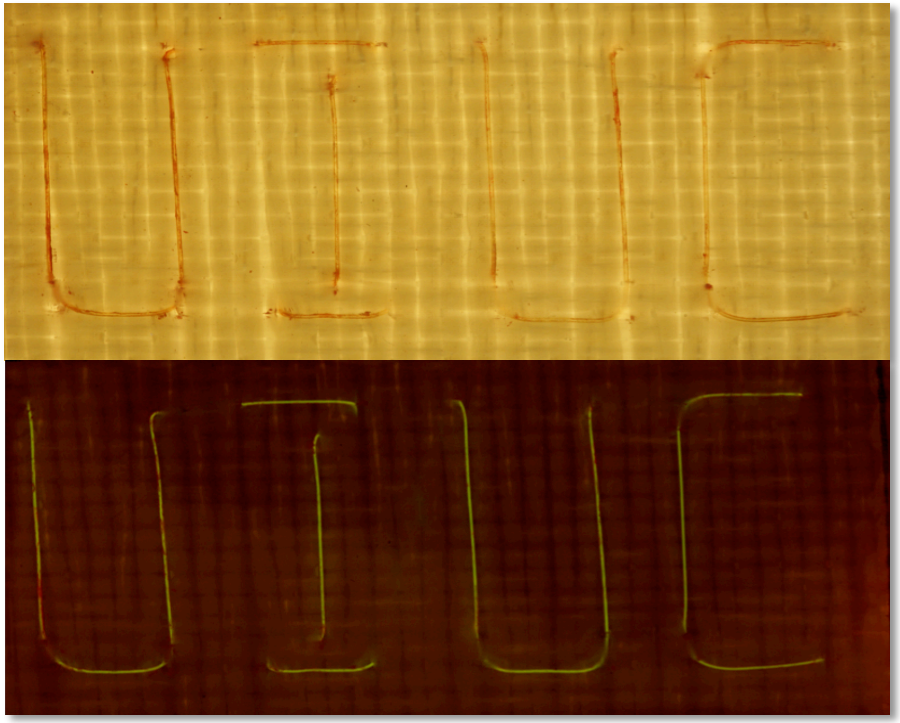






Fibers Can be Woven Into Composite Materials

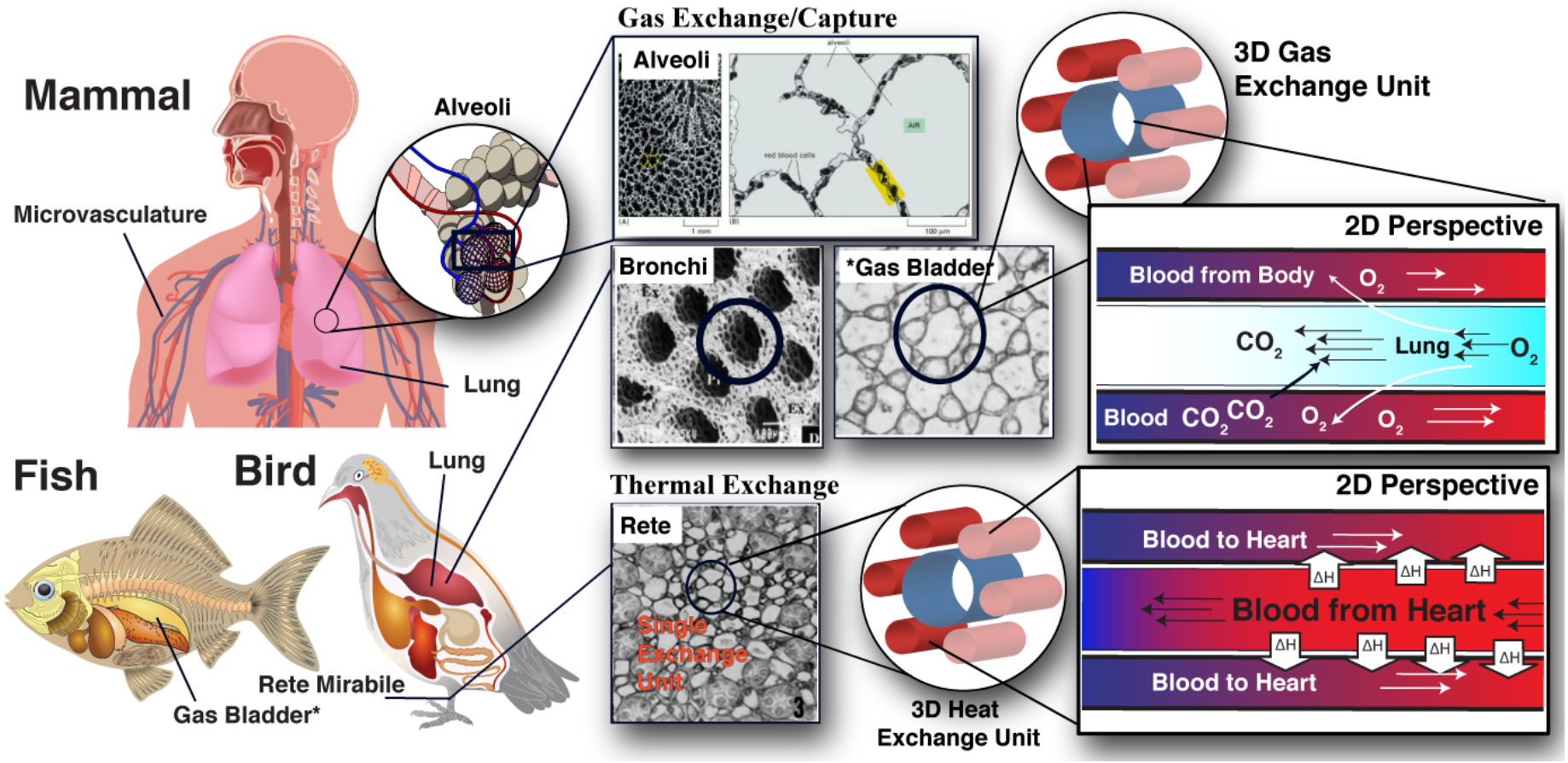
Channel extends over 0.5 meter!



And Deformed to Complex Geometries

Esser-Kahn, A. P.; Thakre, P. R.; Dong, H.; Patrick, J. F.; Vlasko-Vlasov, V. K.; Sottos, N. R.; Moore, J. S.; White, S. R. *Advanced Materials* ***2011, 23, 3654–3658***

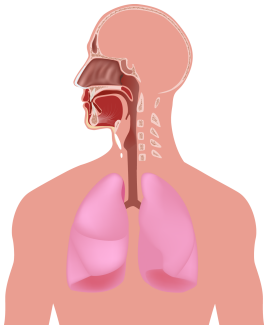
Nature: A brilliant chemgineer



In Nature Thermal And Gas Exchange Are Based On Same Structures

Just how efficient are natural structures?

$$\frac{2 \times 10^{12}\ KwH \bullet yr^{-1}}{85 \times 10^{10}\ L \cdot CO_2 \cdot yr^{-1}}$$



Breathing Capacity of Lung

Resting $0.5 \cdot L \cdot \min^{-1}$

Max. Cap. $3.0 \cdot L \cdot \min^{-1}$

Lungs are some of the most efficient structures known

=

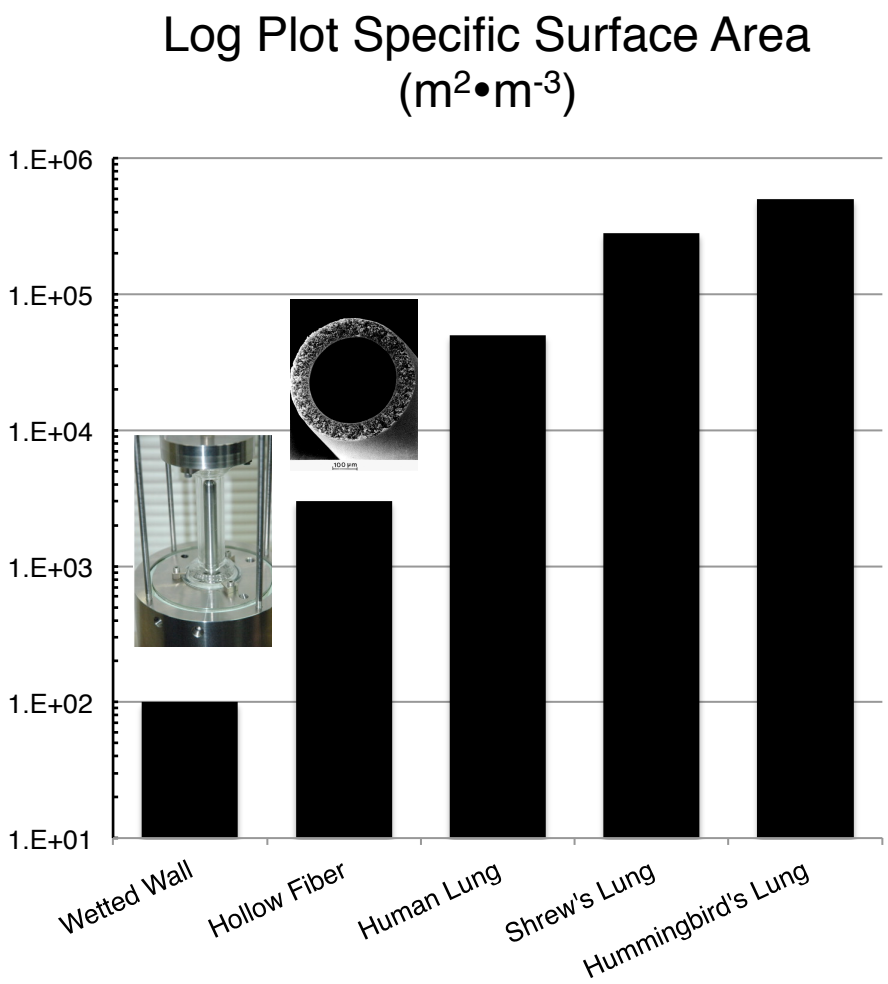
3 million
(0.5 million max cap)

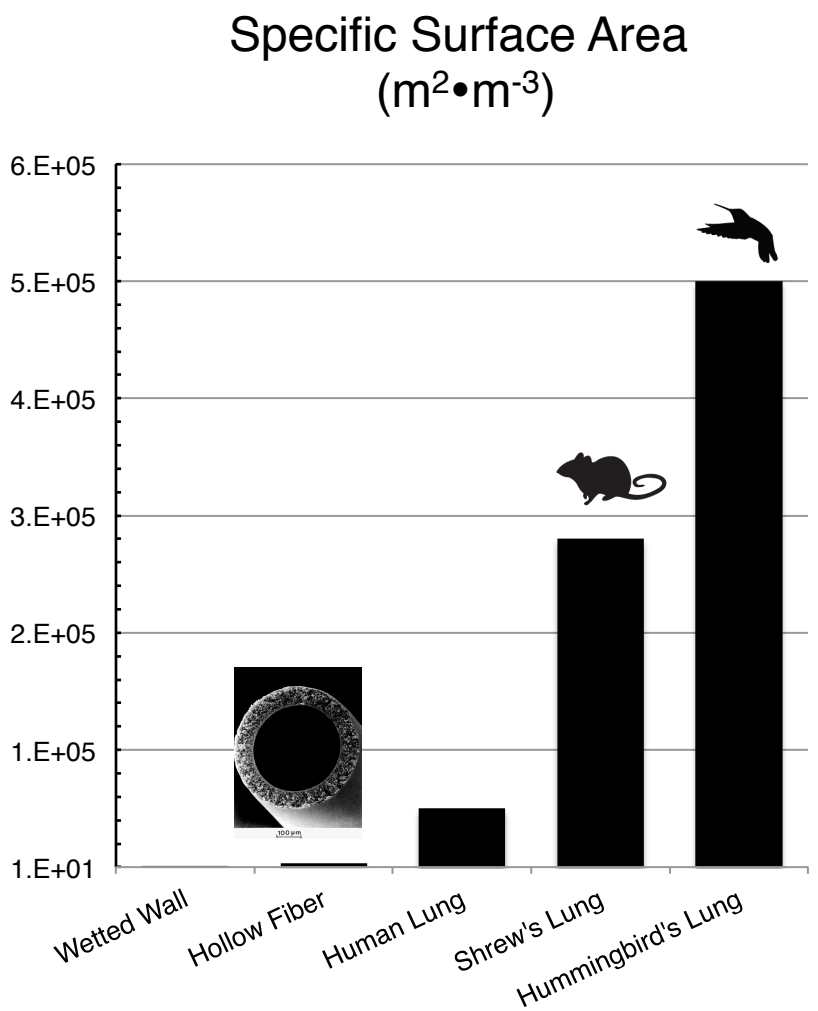
0.1% total energy

DOE, NETL, 2008 CO_2 report

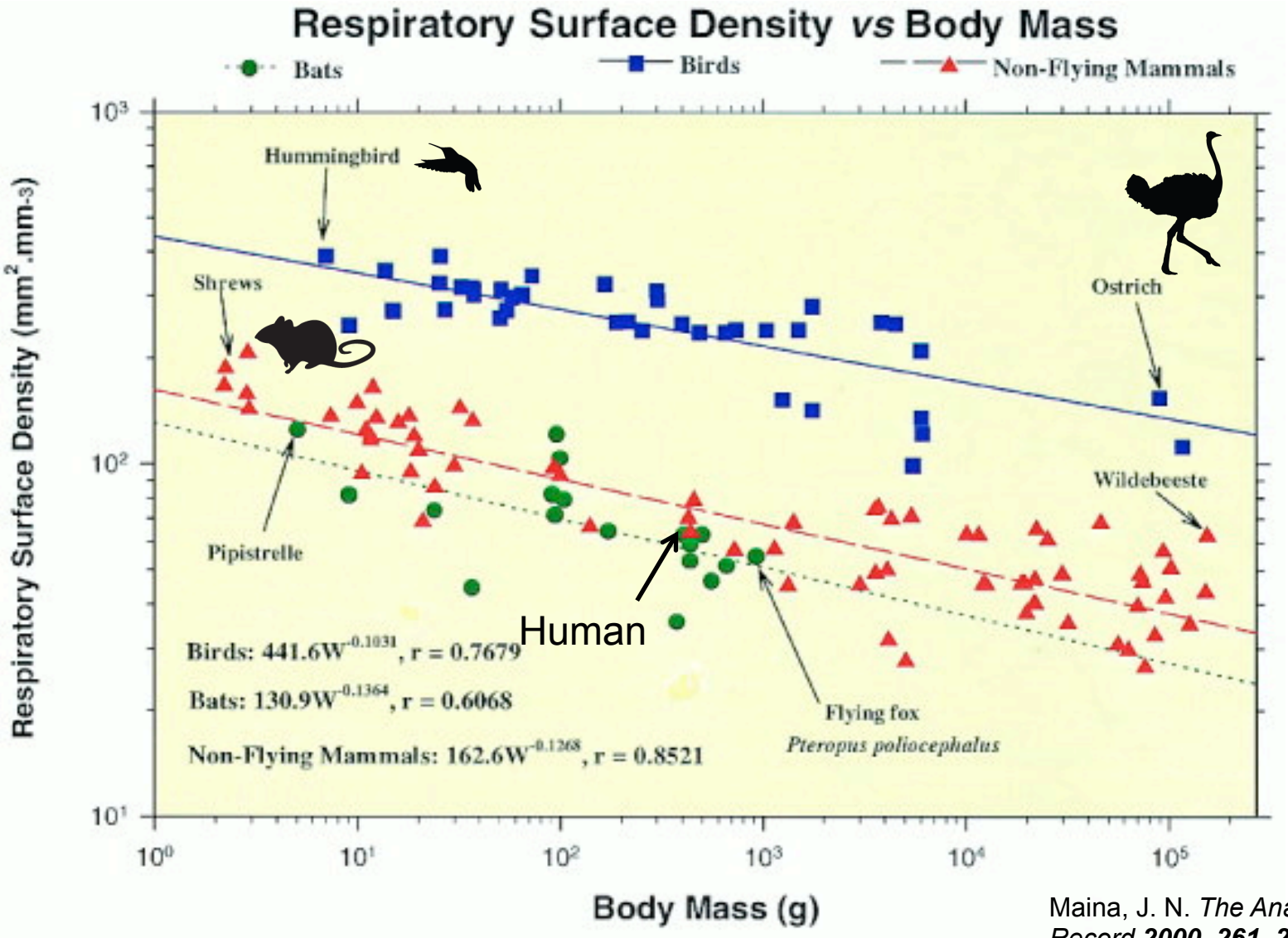
Merck – Lung Guide

Man-Made Exchangers vs. Natural Exchangers



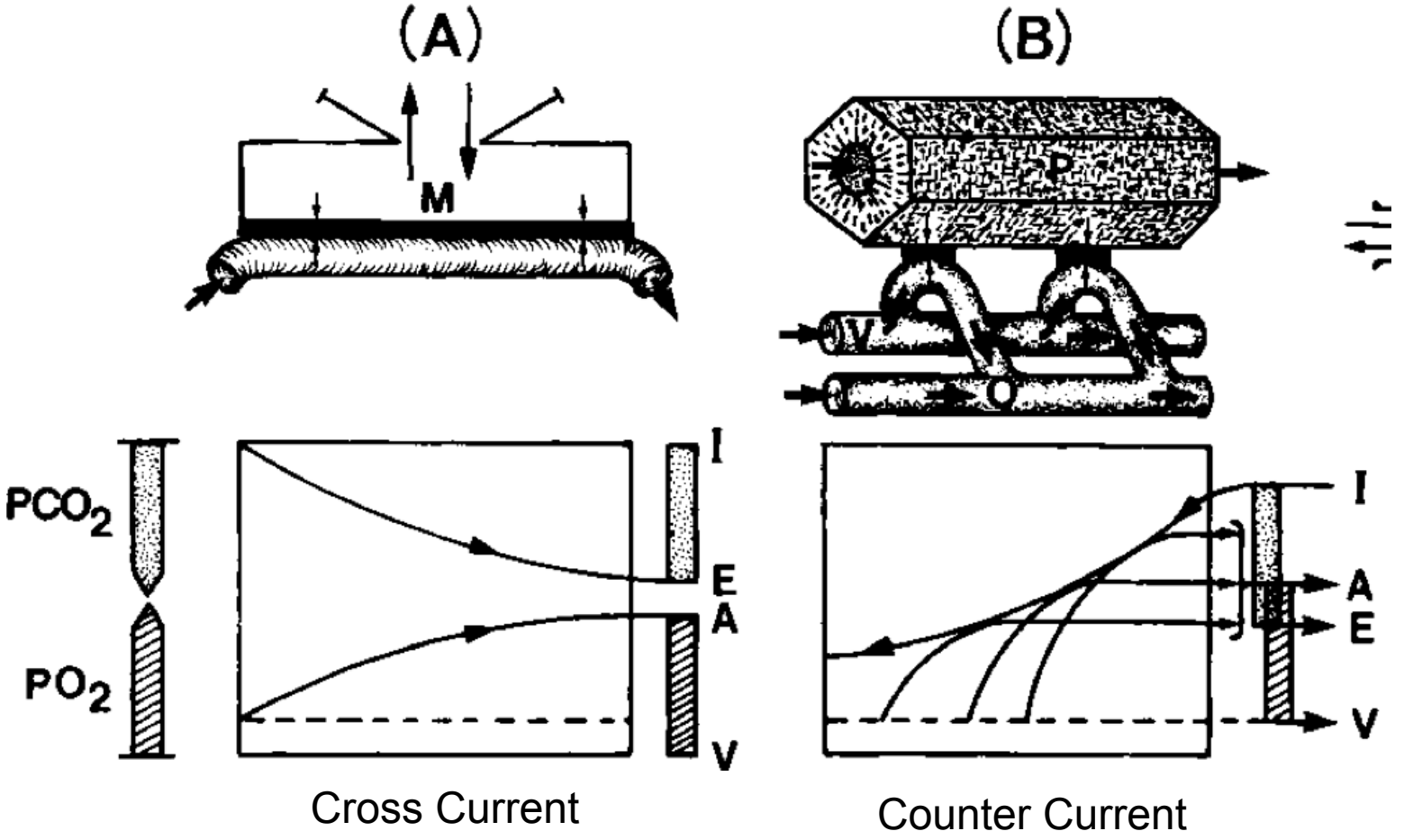


Natural Systems – Scalable Solutions



Maina, J. N. *The Anatomical Record* ***2000, 261, 25–44***

What makes avian lung so appealing?



Cross Current

Counter Current

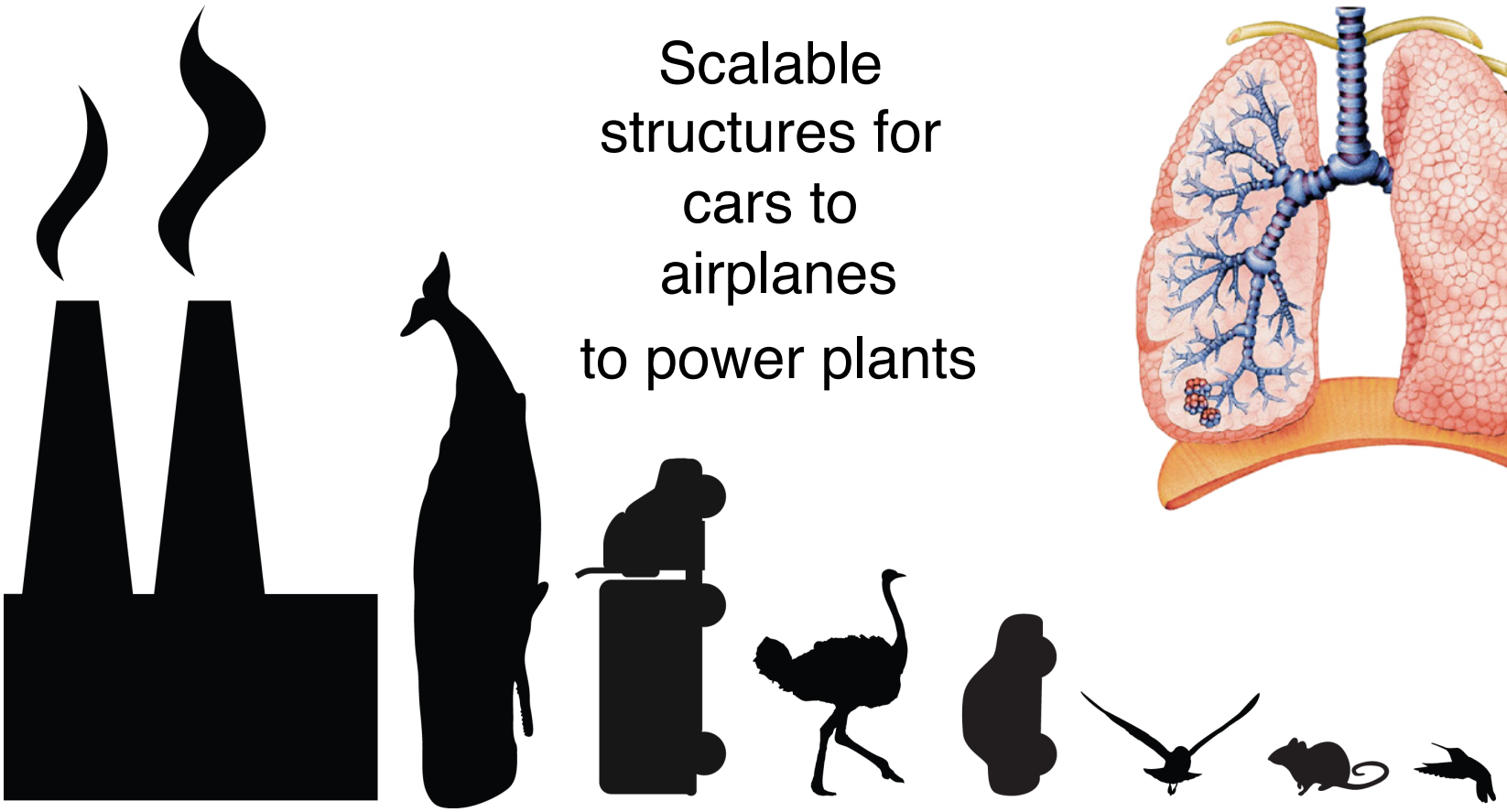
Building A Model Exchange Unit

Each system has single, repeating Exchange Unit

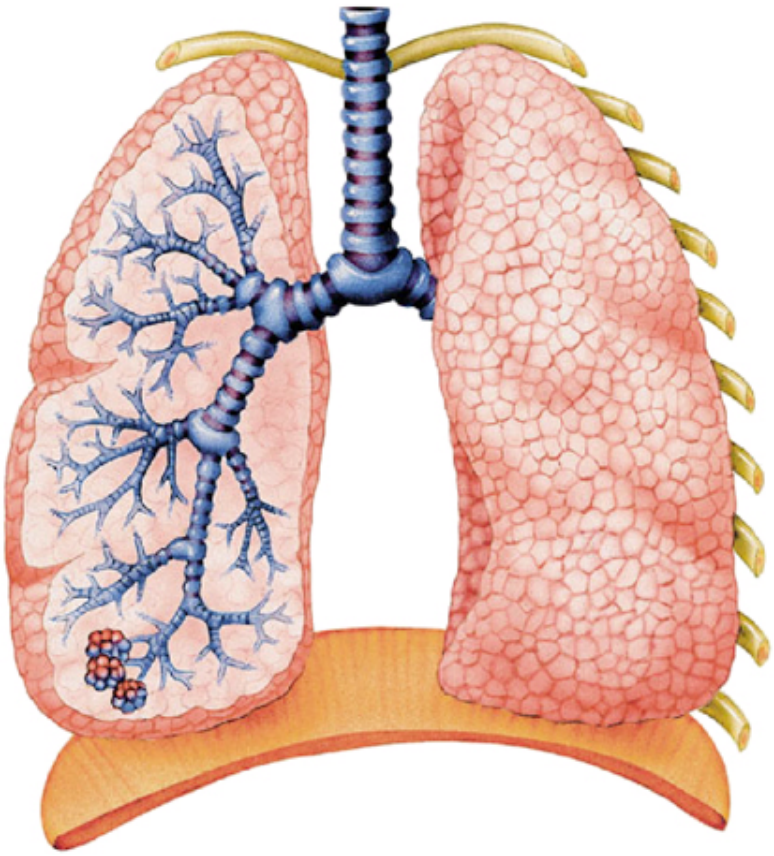
Our Goal: *Develop Optimized Gas Exchange Unit*

Scalable structures for cars to airplanes

to power plants

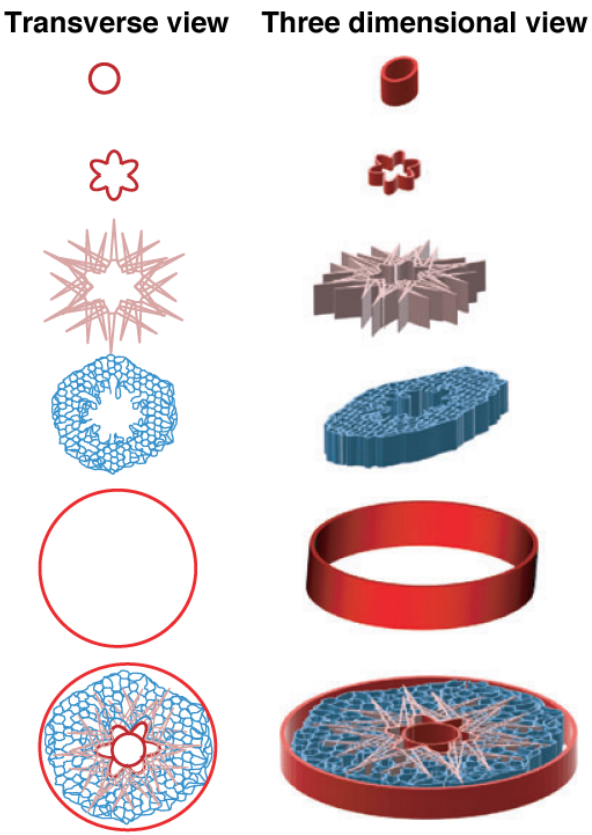


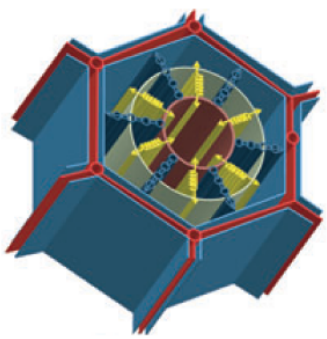
Applicable Properties of Natural System

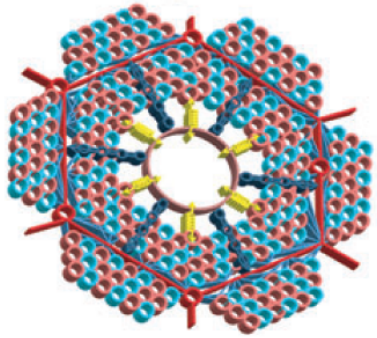


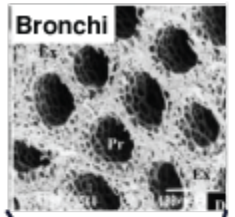
- Surface Area
  - 3D arrangement
- Surface Chemistry
- Hierarchical Arrangement
- Compartmentalized Transfer
  - Heat transfer
  - Mass Transfer

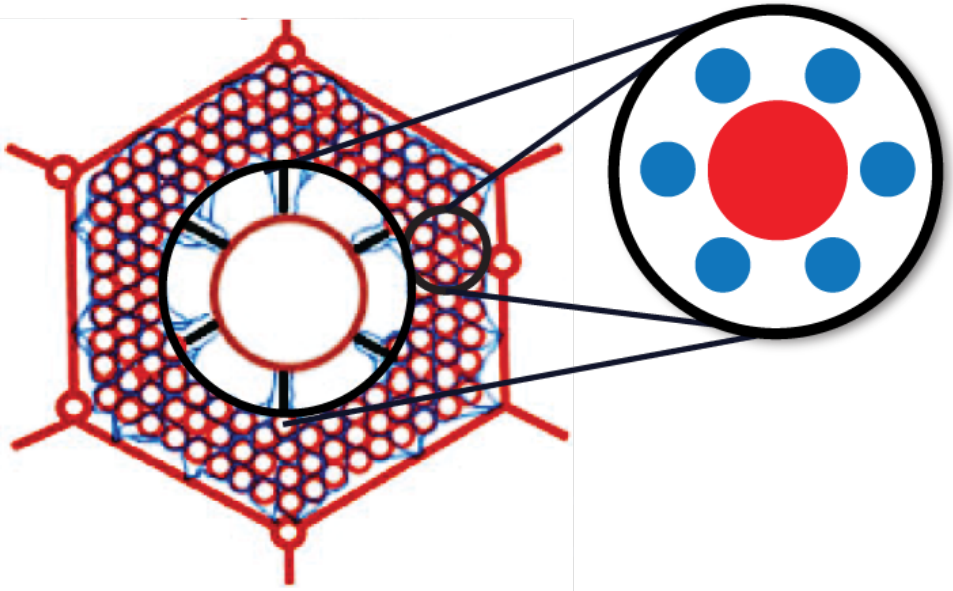
What will our exchange unit look like?







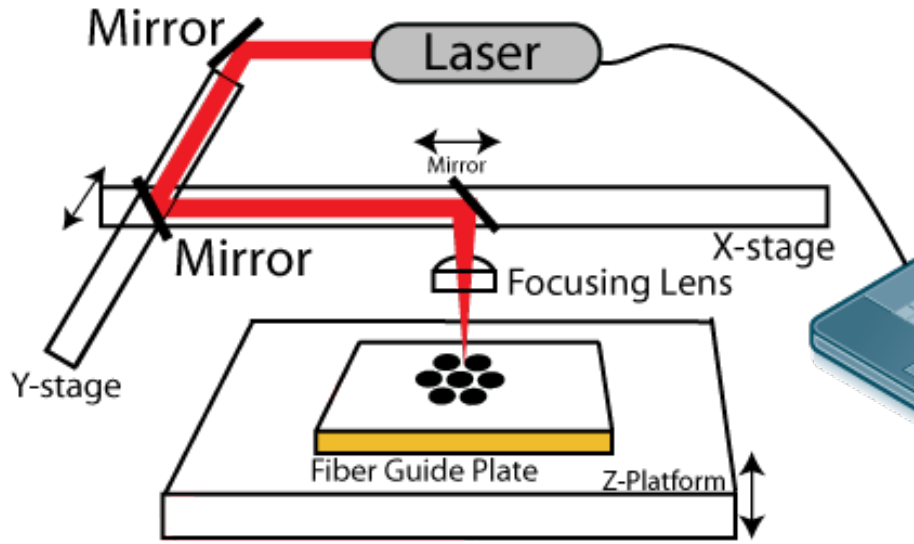




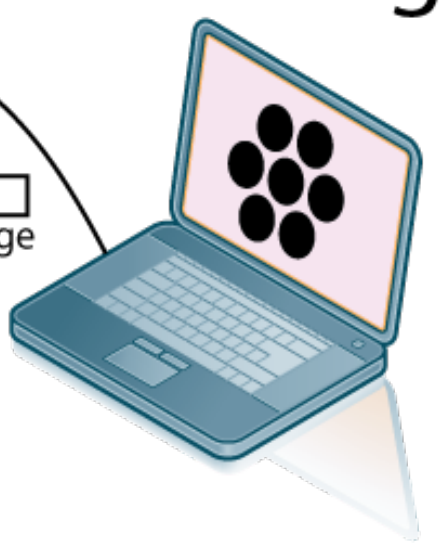
We Needed A Way to Create An Experimental Platform for Exploring Structure!

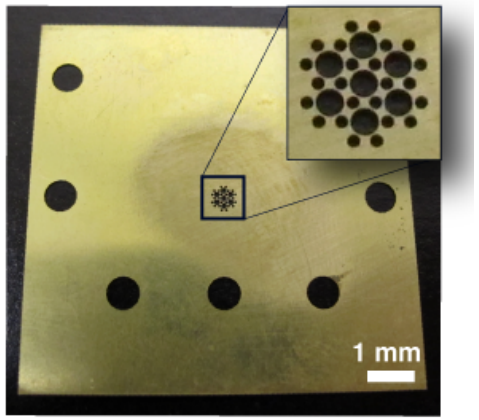
Making an Exchange Unit

Computer Aided Micro-Machining

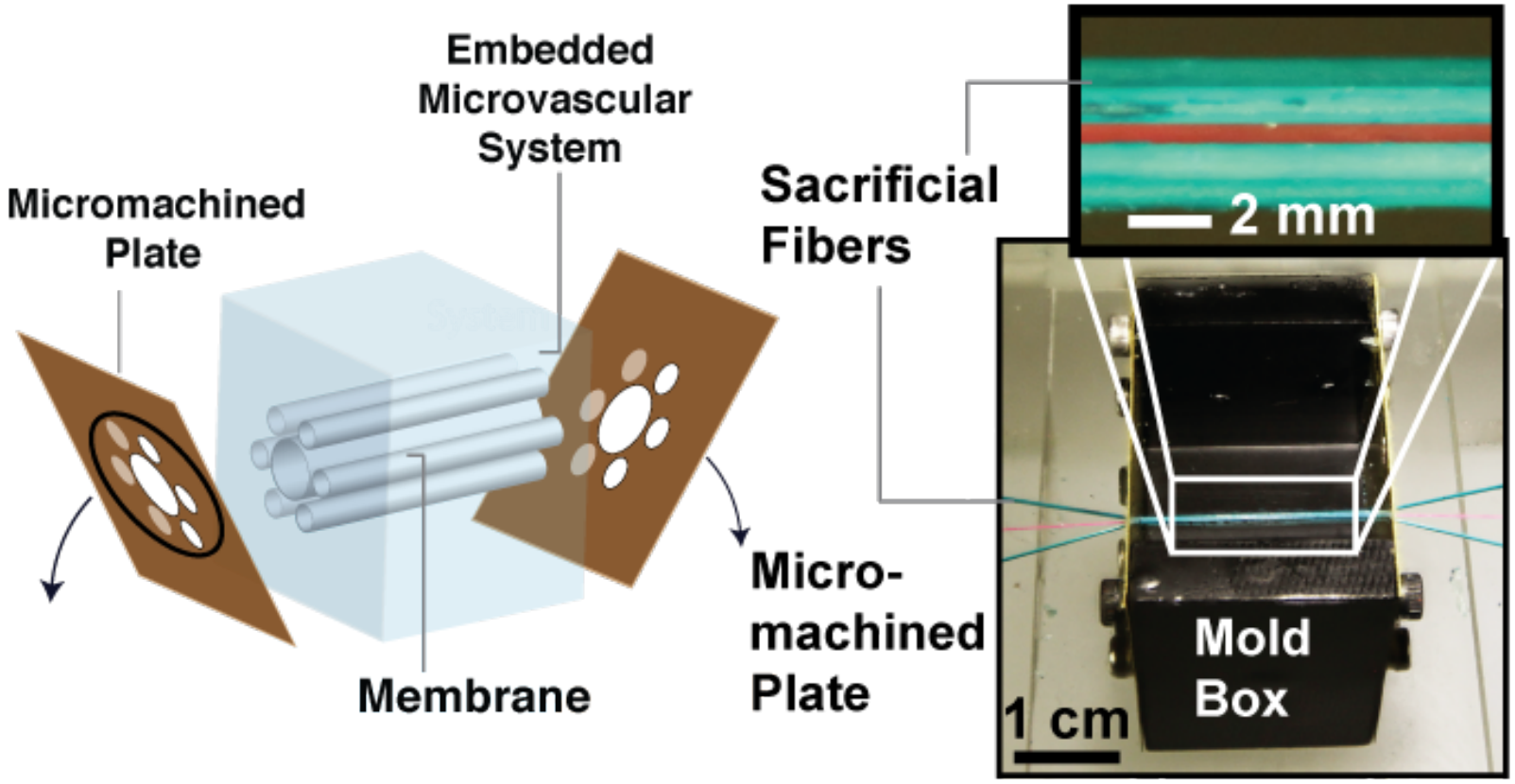


AutoCAD Design

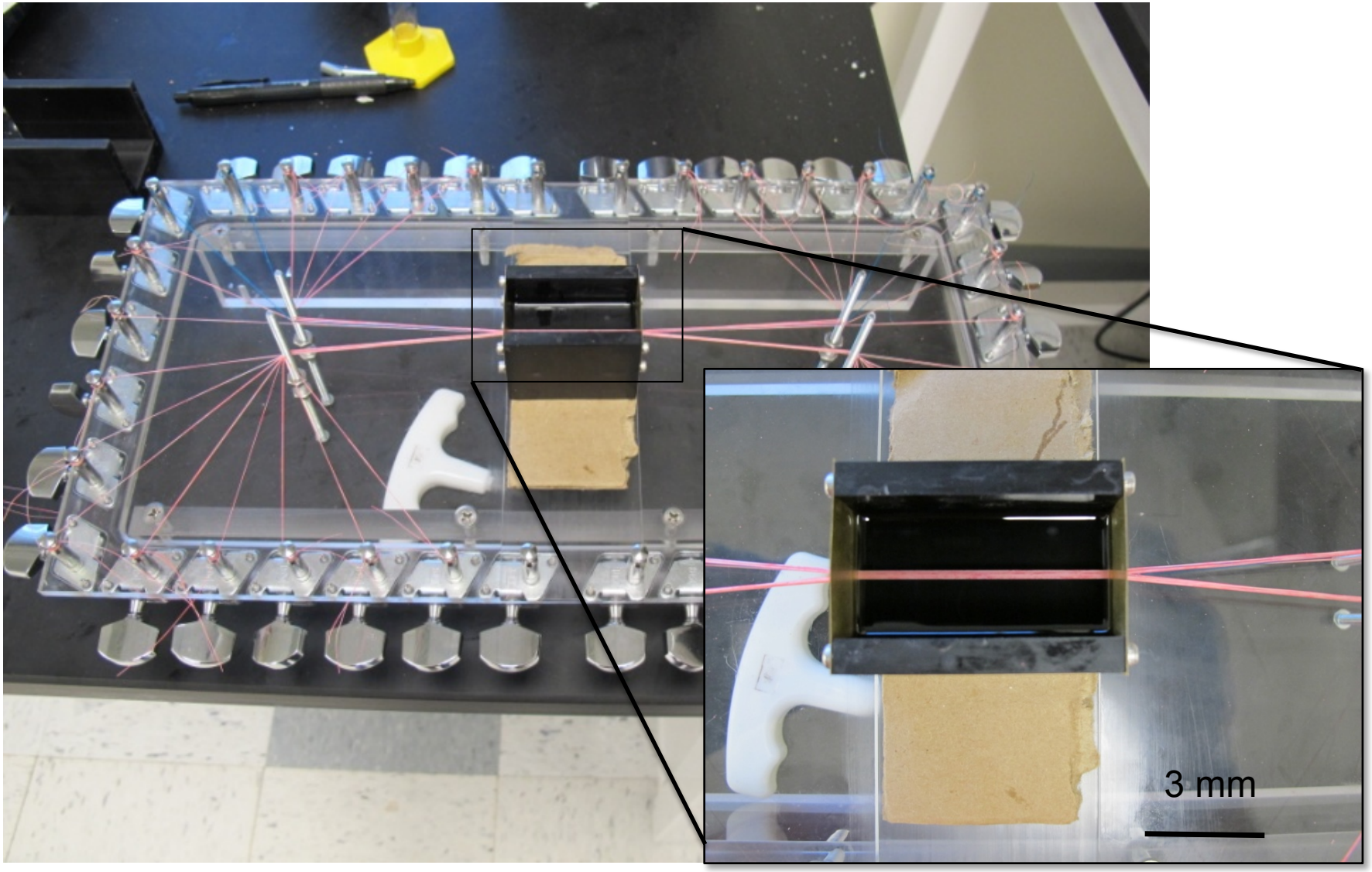




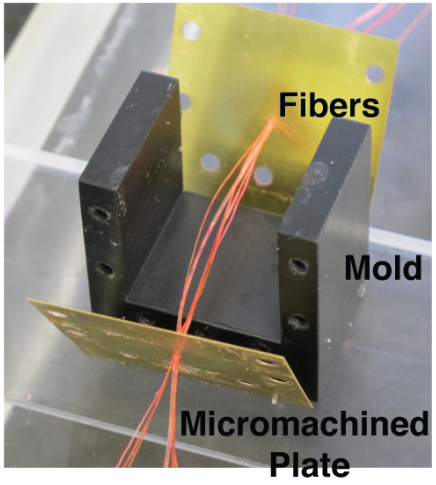
Patterning An Exchange Unit

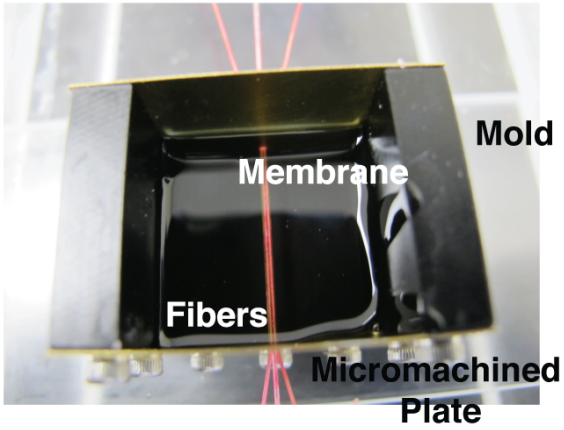


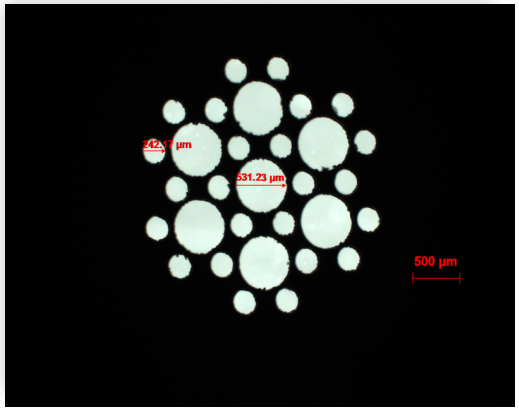
Established Fiber Tensioning Technology

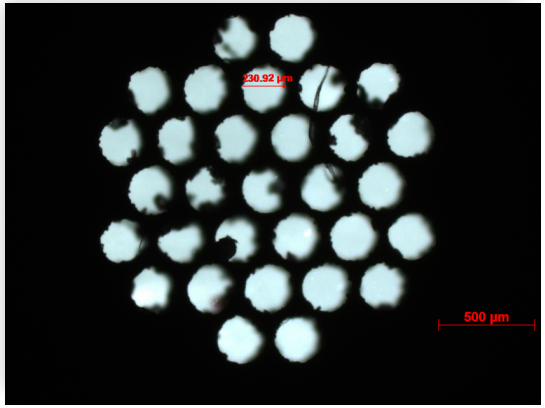


Replication molding of natural patterns in 3D







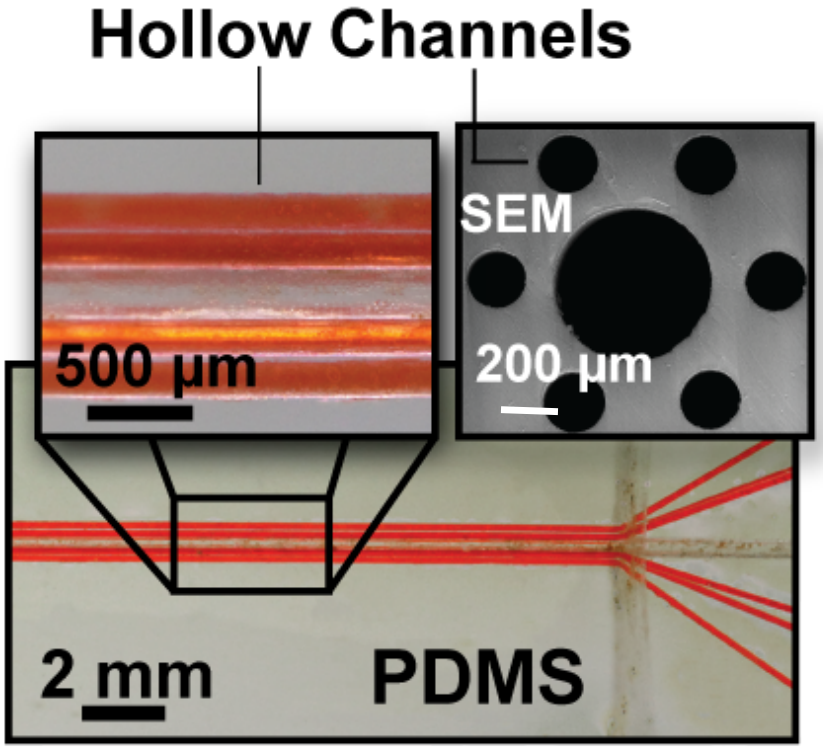


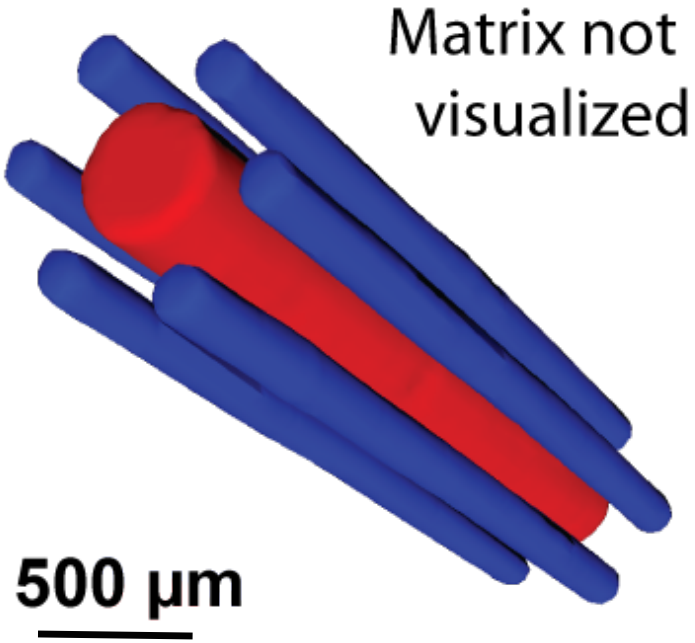
500 microns

Micro CT

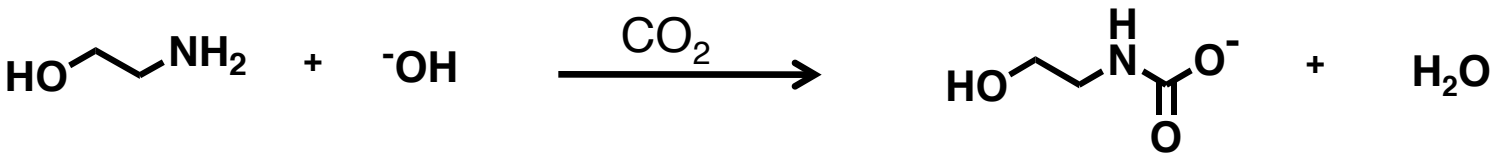
Not Model

Analysis of Replication Molding





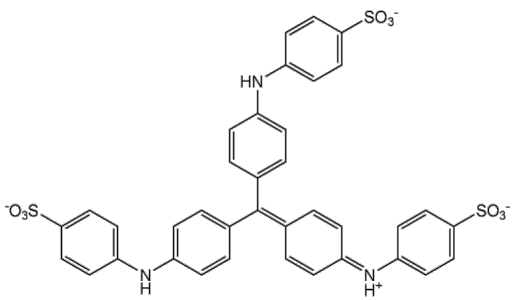
Observing Transfer In Exchange Unit



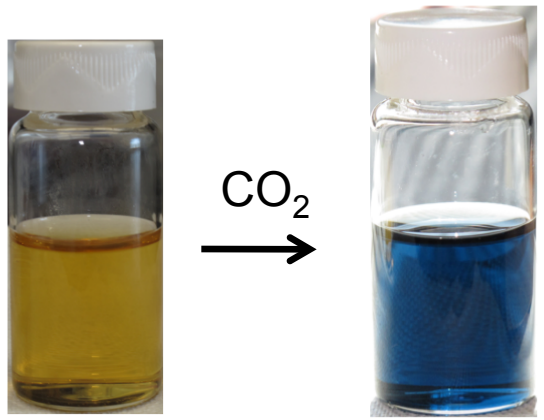
pH ~ 12

30% w/w in H_2O

pH 12 **pH 8**



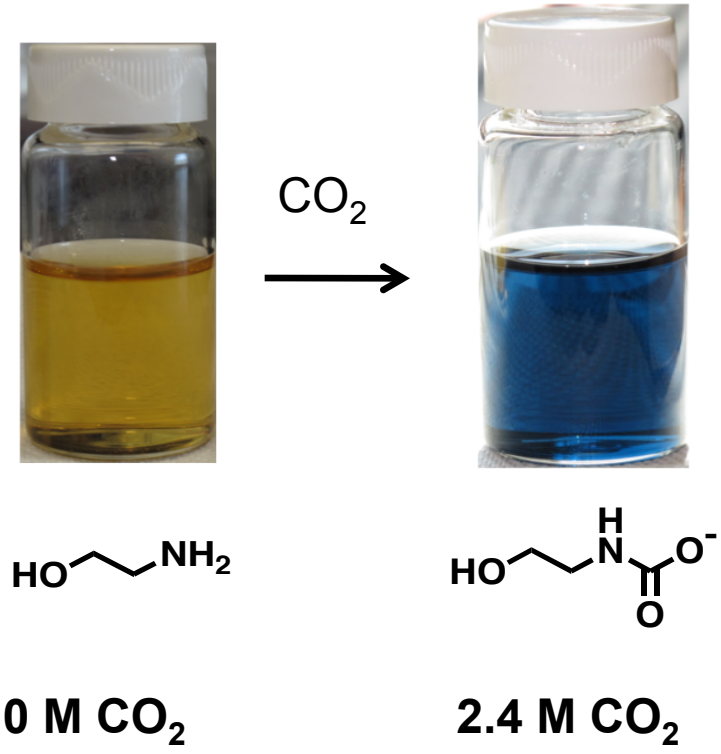
Methyl Blue

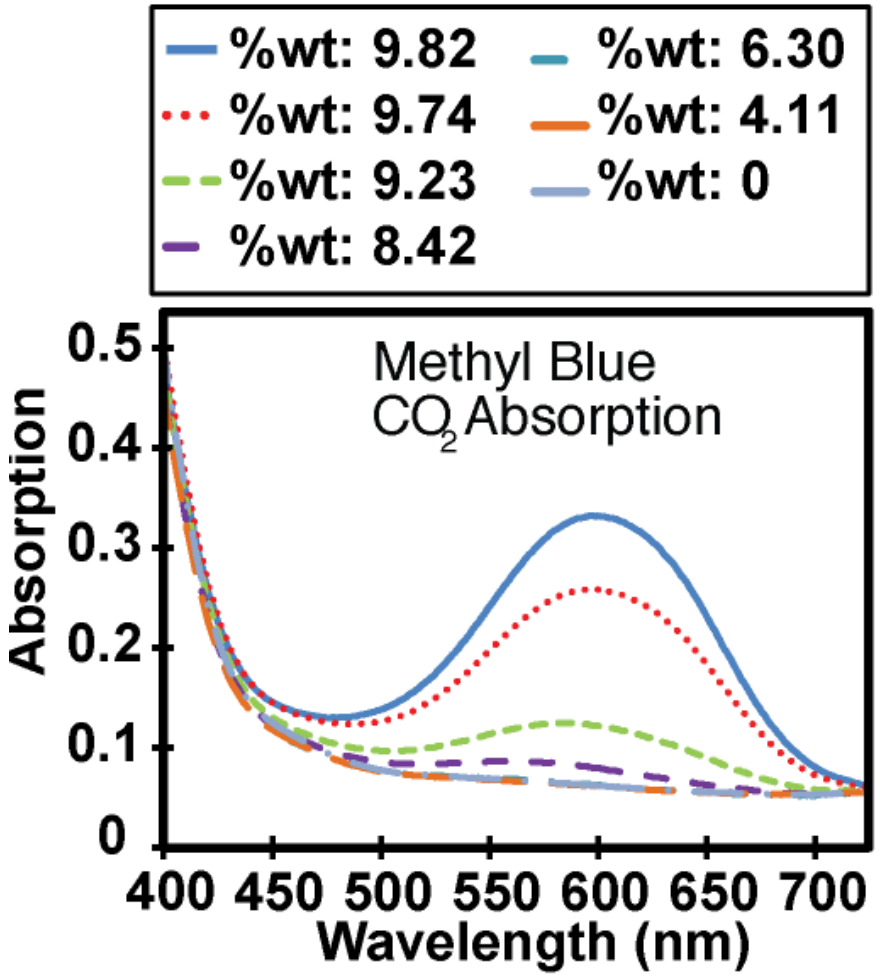


Color changing reaction can be used to quantify rate of transfer

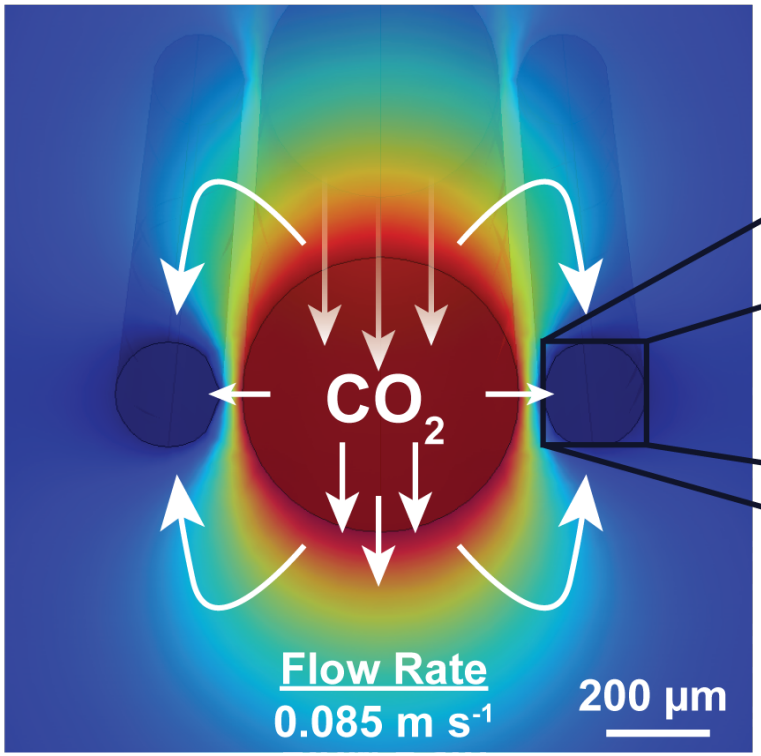
Blue = 10 w%

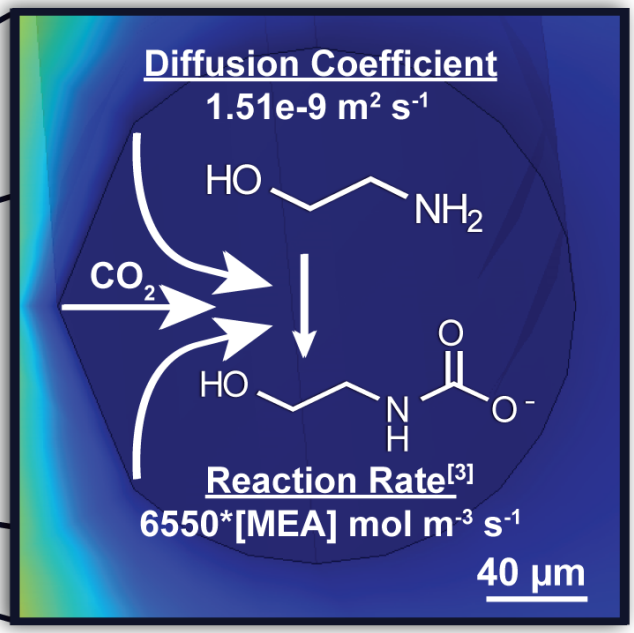
Observing CO_2 Absorption

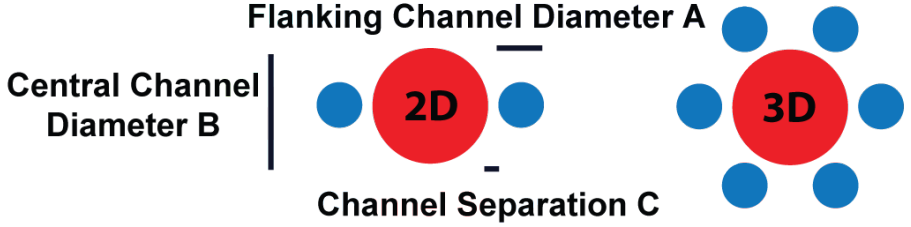




Modeling to Understand Experiment





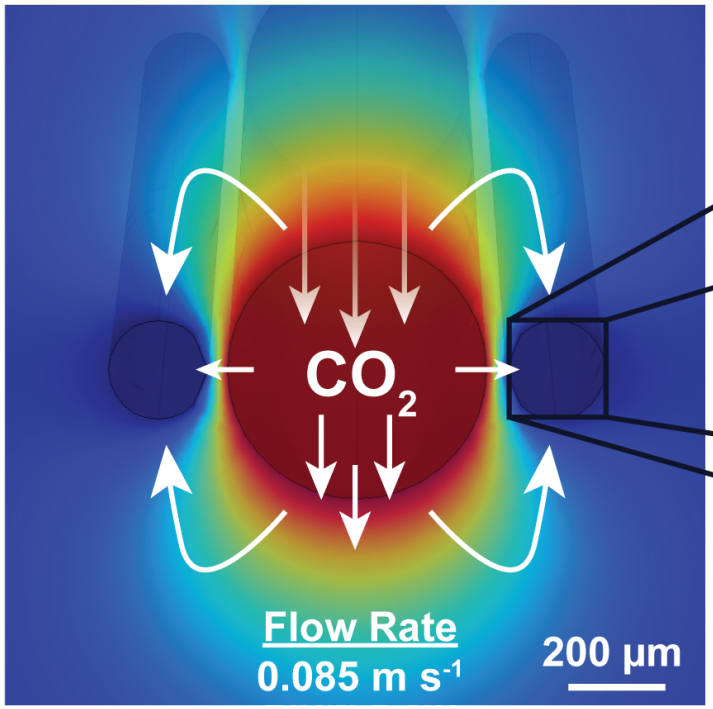


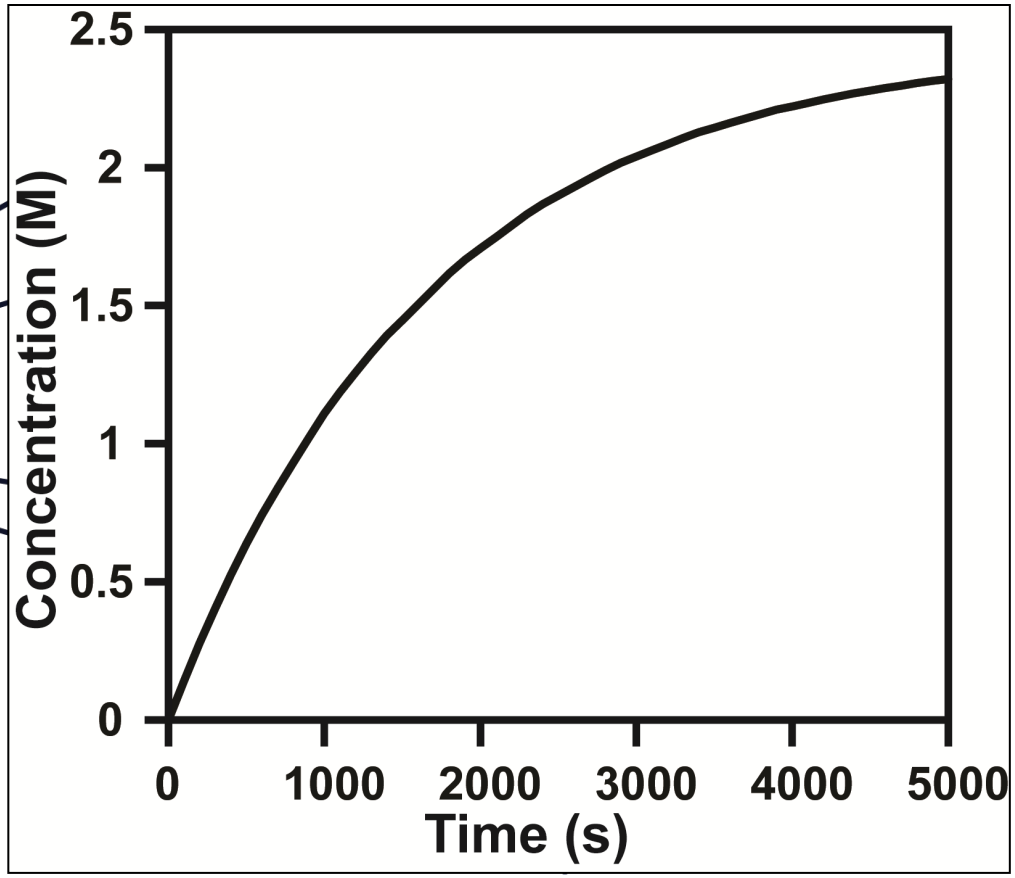
Dang, H.; Rochelle, G. T. Separation Science and Technology 2003, 38, 337.

Maceiras, R. Álvarez, E.; Cancela, M. Á. Chem. Eng. J. 2008, 138, 295-300.

Merkel, T. C. Bondar, V. I. Nagai, K. Freeman, B. D.; Pinnau, I. J. Polym. Sci., Part B: Polym. Phys. 2000, 38, 415-434.

Modeling to Understand Experiment



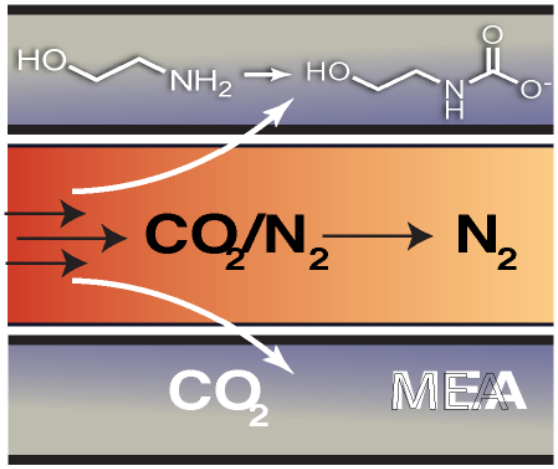


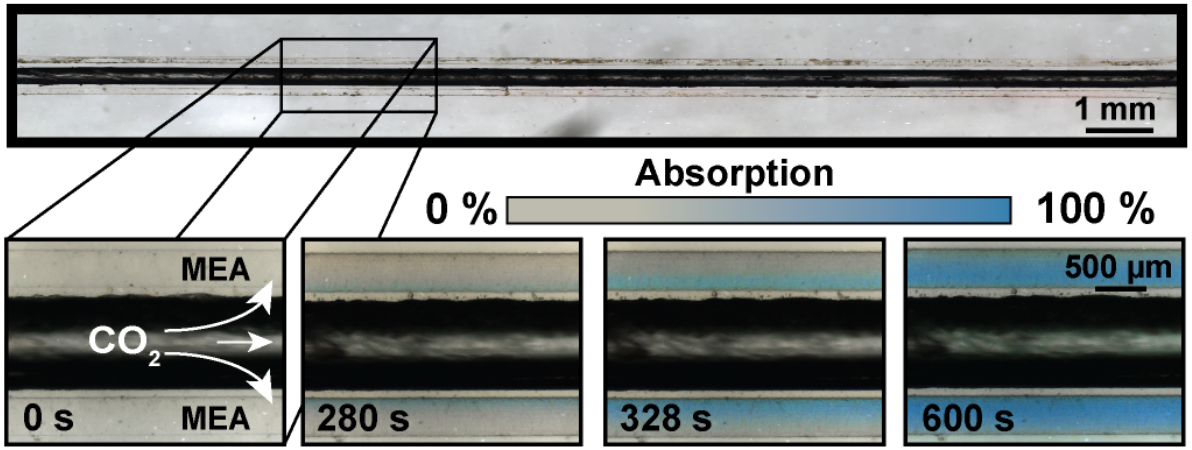
Dang, H.; Rochelle, G. T. Separation Science and Technology 2003, 38, 337.

Maceiras, R. Álvarez, E.; Cancela, M. Á. Chem. Eng. J. 2008, 138, 295-300.

Merkel, T. C. Bondar, V. I. Nagai, K. Freeman, B. D.; Pinnau, I. J. Polym. Sci., Part B: Polym. Phys. 2000, 38, 415-434.

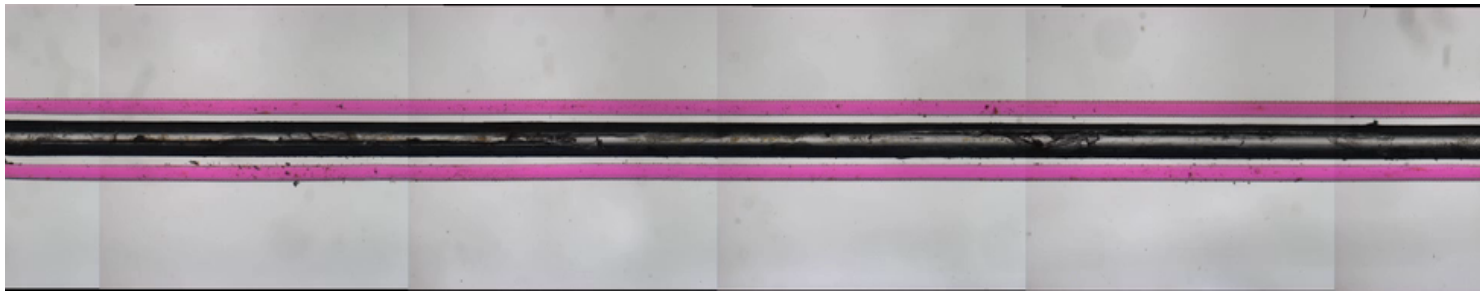
Spatio-Temporal Nature of Reaction



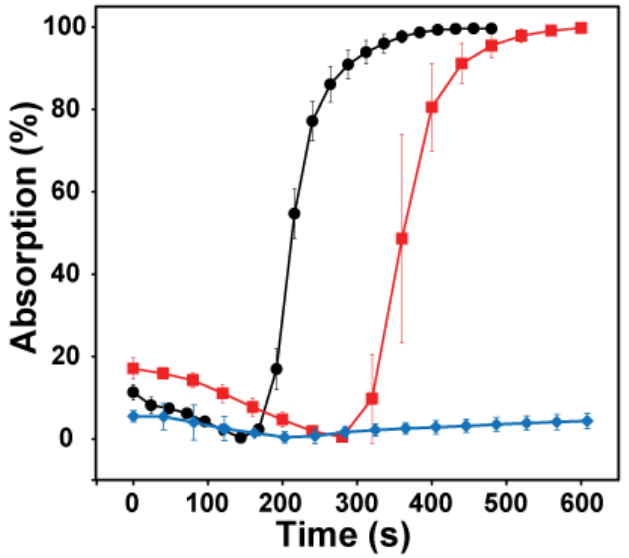


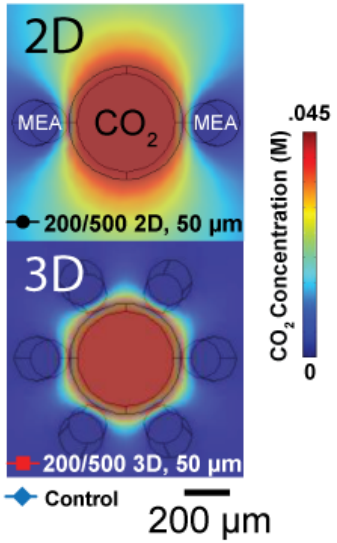
CO_2 Saturated Solution (pH ~8)

Empty (pH ~13)



2D vs. 3D : Visualizing Reacivity



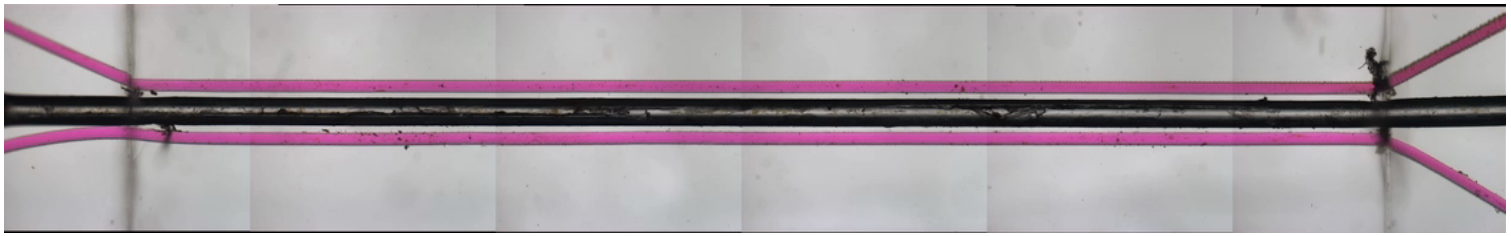


Mass Transfer Rate
Pure CO_2

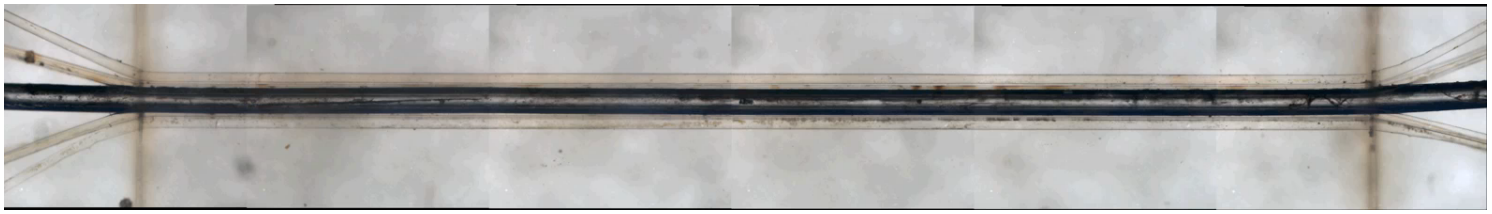
1.66 ± .17 mol/m^2 hr

2.96 ± .35 mol/m^2 hr

2D



3D



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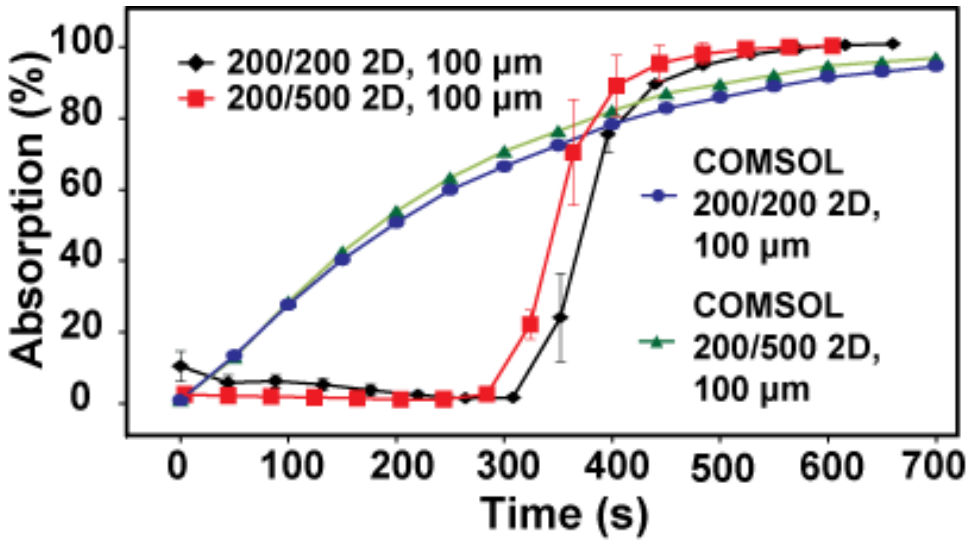
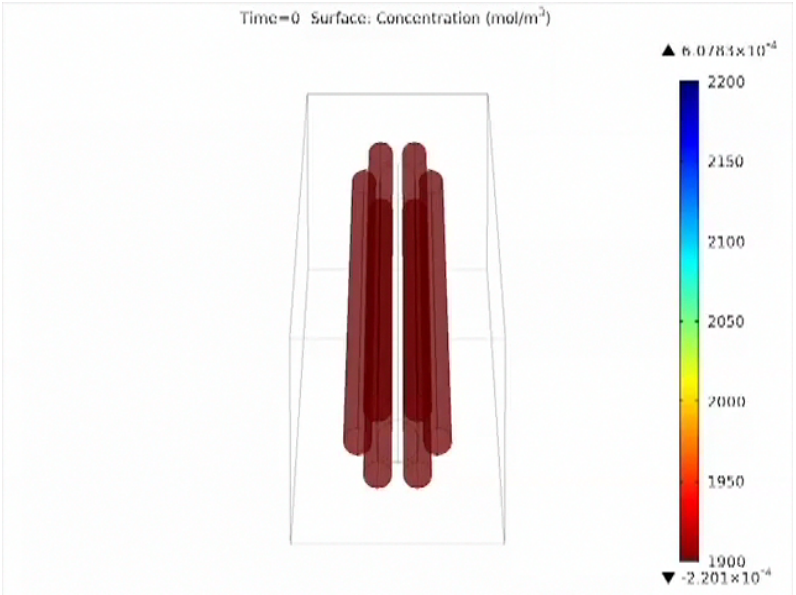
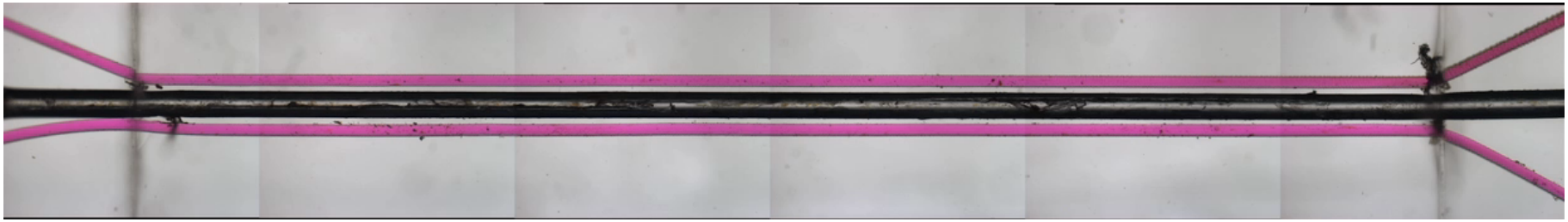
Matching Modeling and Experiment







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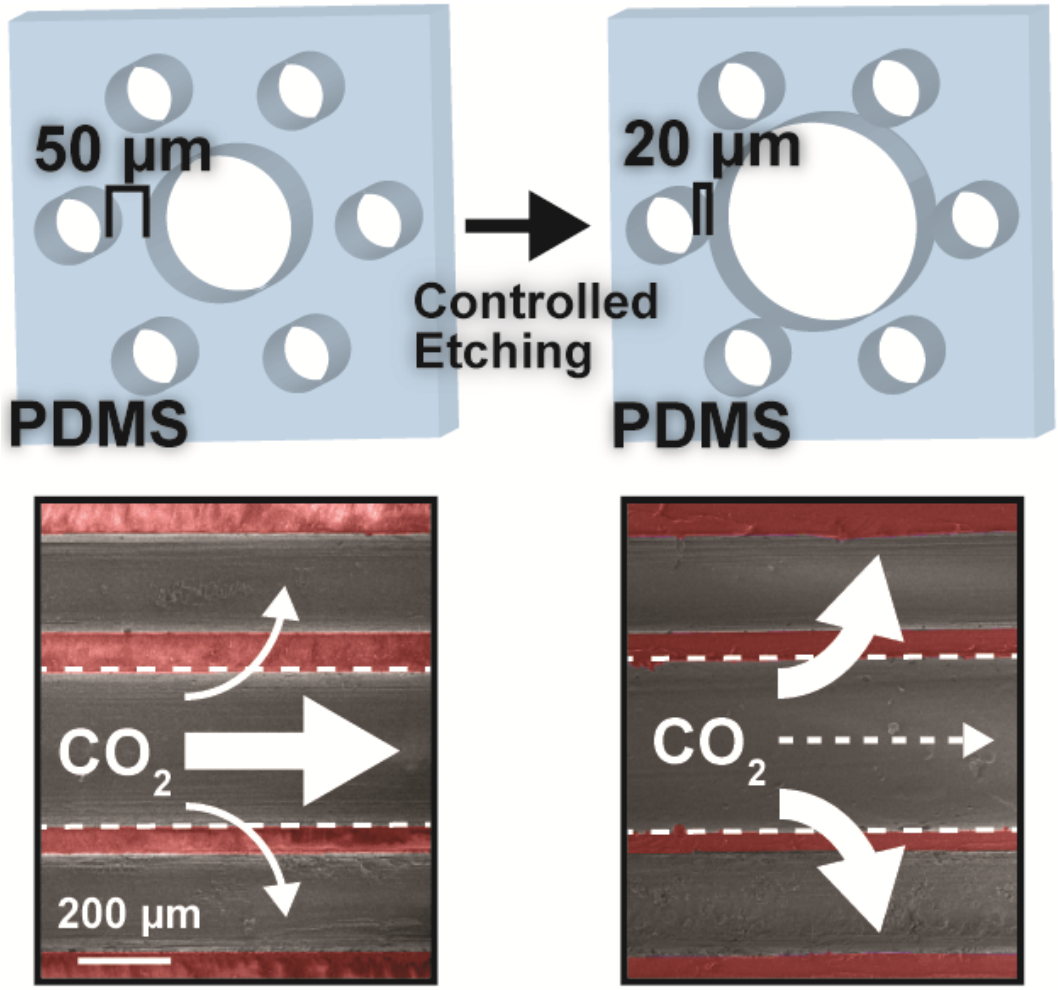
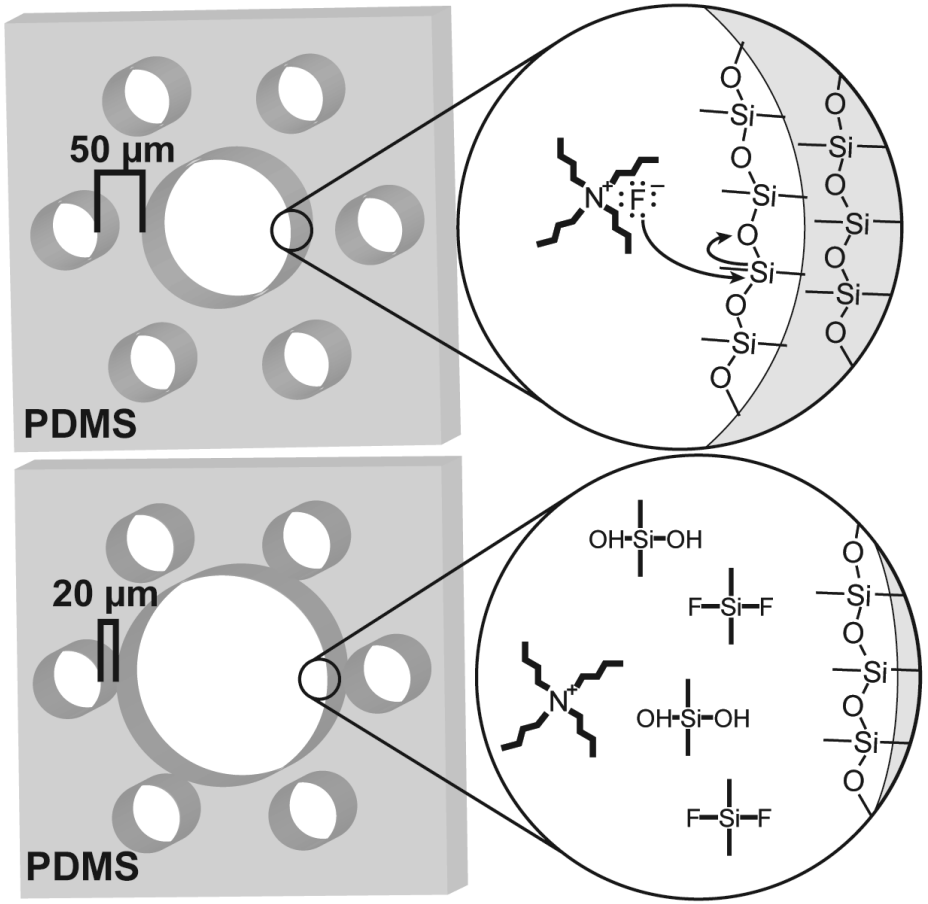
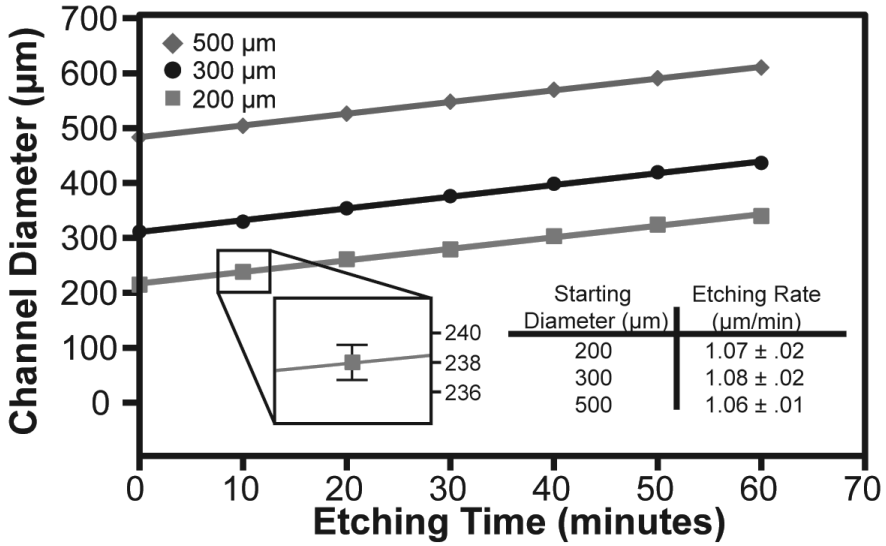
Controlling Transfer By Changing Unit Geometry



Etching with Micron Precision

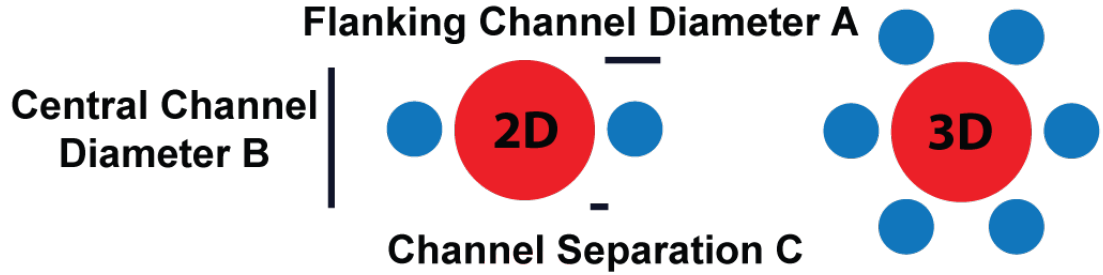


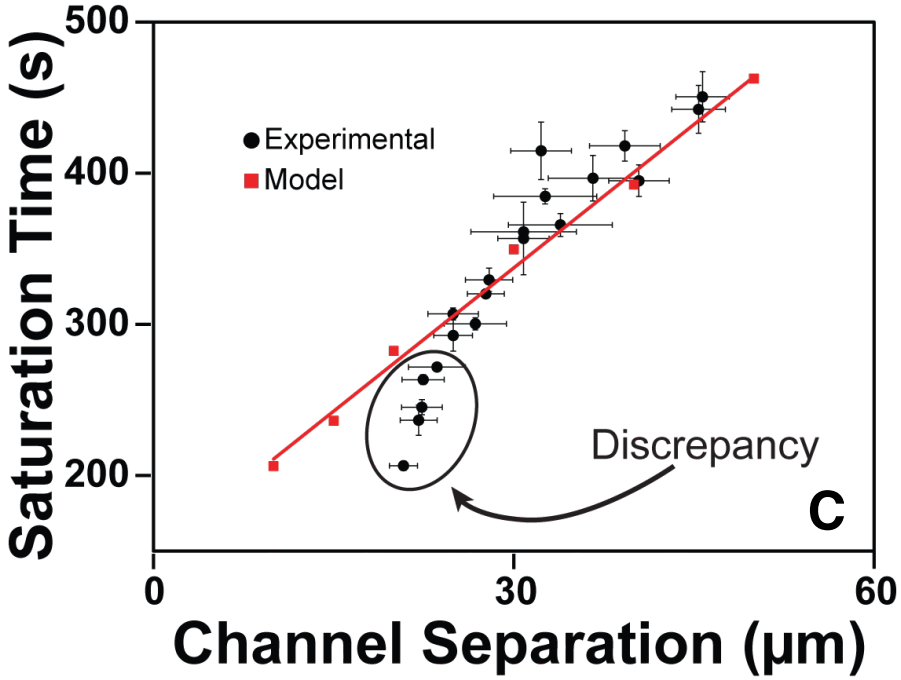


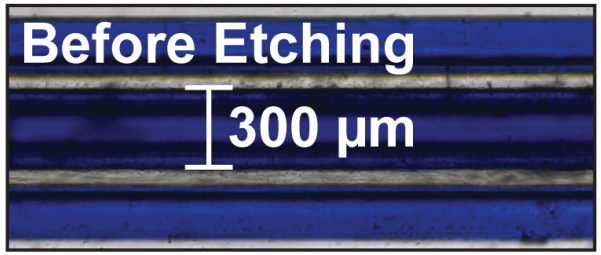
Flow Rate (mL min $^{-1}$)	Etching Rate (µm min^{-1})
2.00	1.07 ± .03
1.00	0.97 ± .02
0.50	1.06 ± .01
0.25	0.85 ± .03

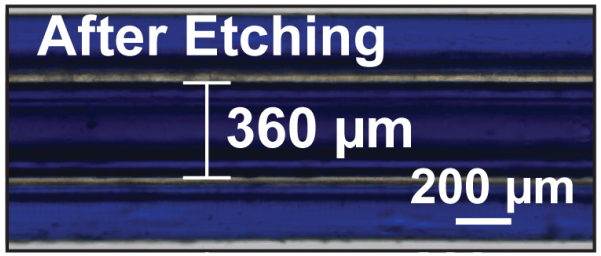
S. Takayama, E. Ostuni, X. Qian, J. C. McDonald, X. Jiang, P. LeDuc, M. -H Wu, D. E. Ingber, G. M. Whitesides, *Adv. Mat.* **2001**, *13*, 570–574

Controlling Channel Separation



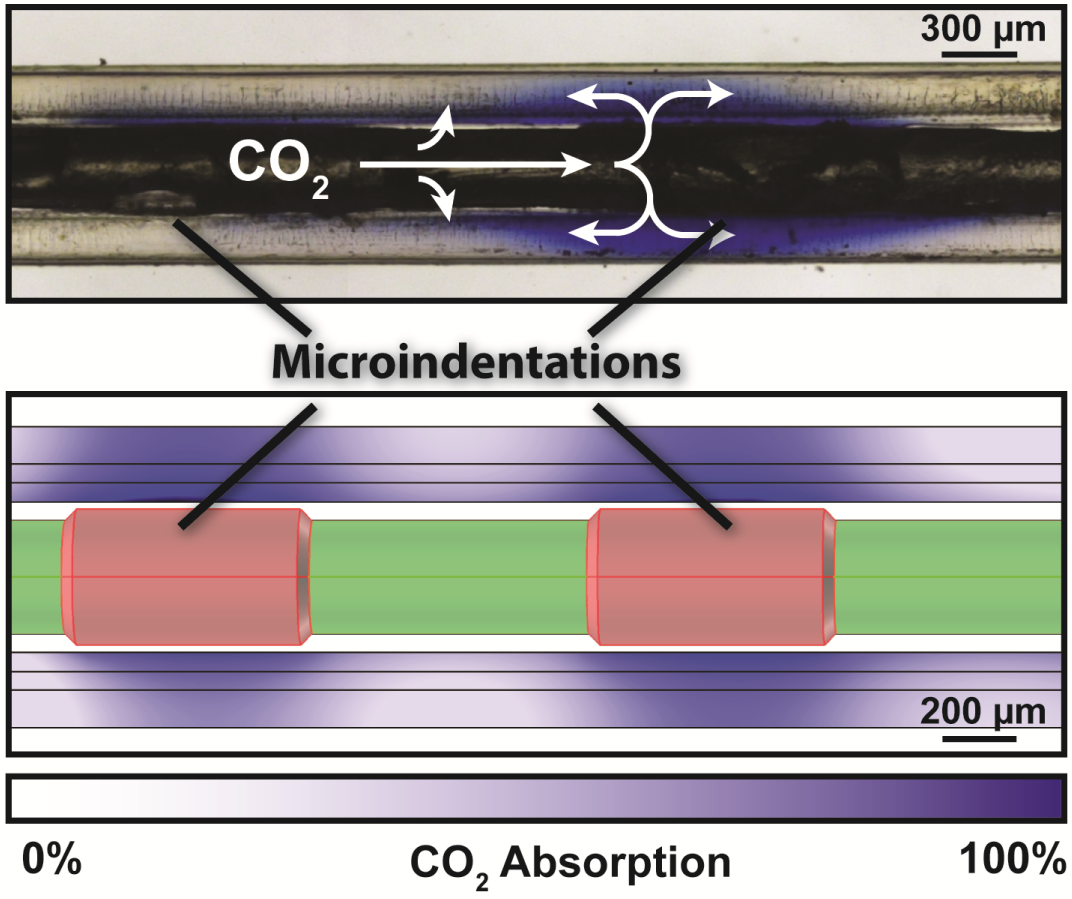


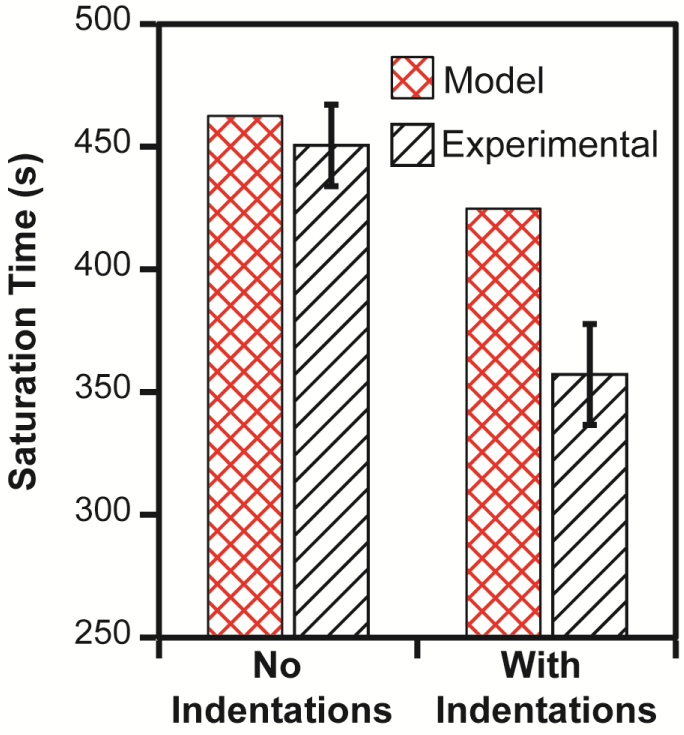




Etching Allows Control Over Reaction Rate

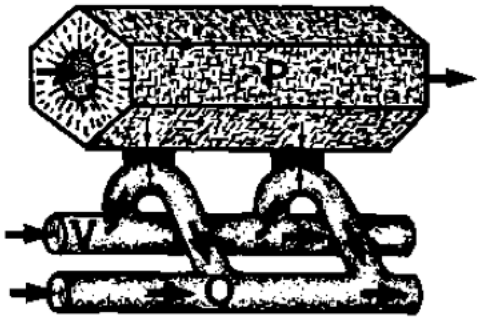
Modeling Reveal Micro-Indents are Key

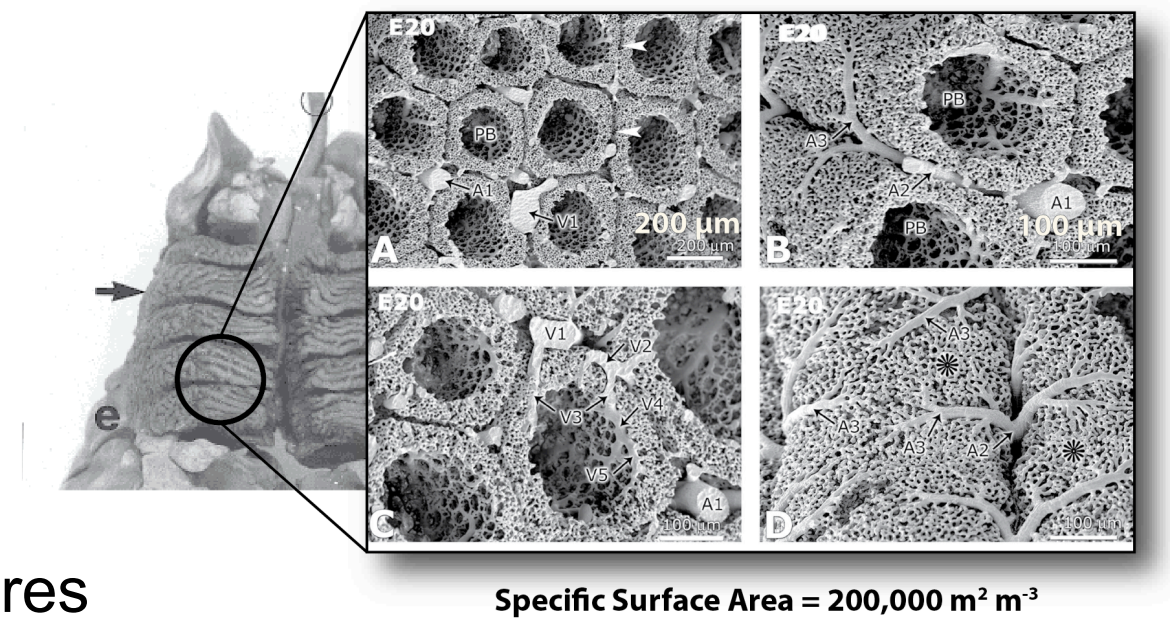




Nguyen, Leho, Esser-Kahn, A. P. Advanced Functional Materials, 2012, ASAP

How do we get to here?



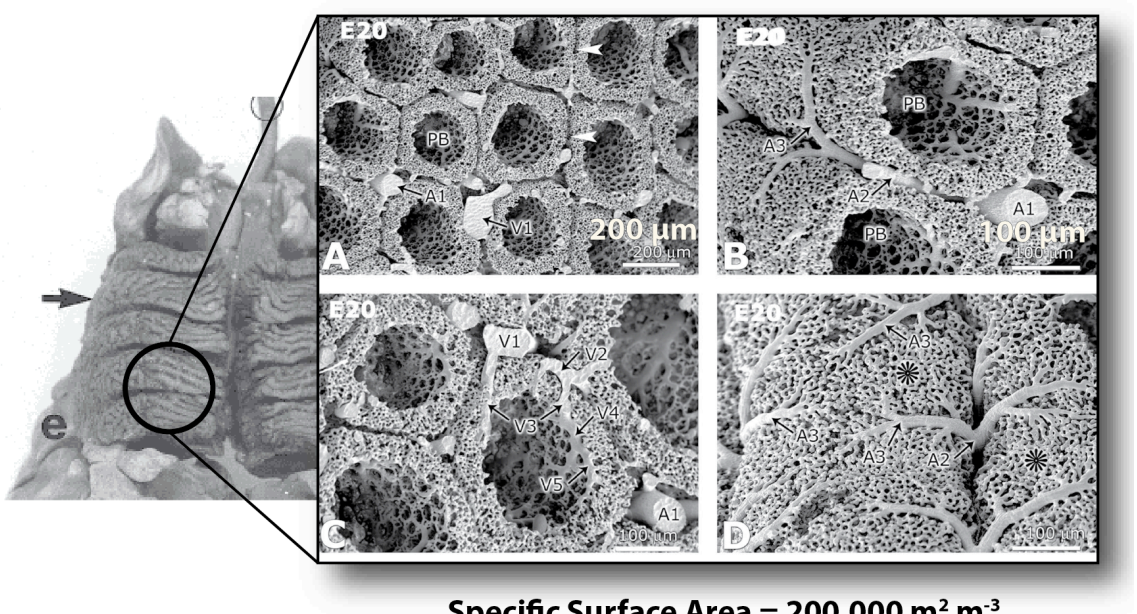


More Complex Structures

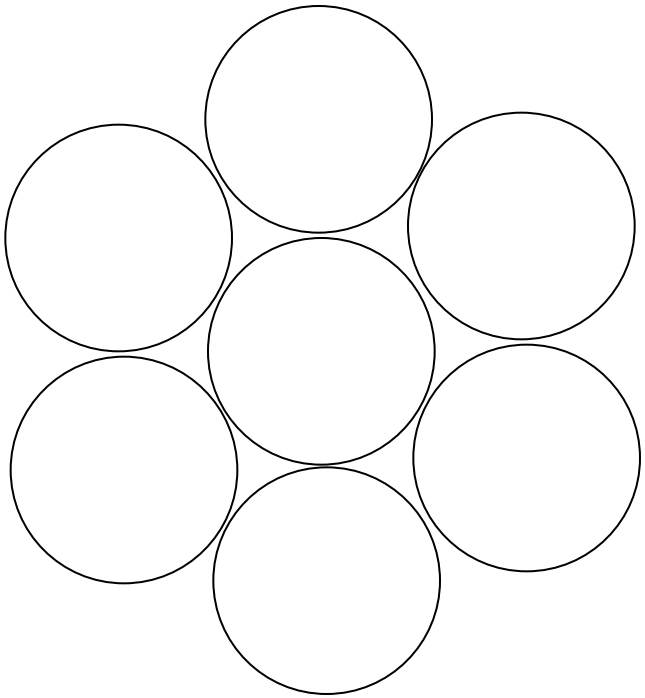
Specific Surface Area = 200,000 m^2 m^{-3}

i.e) What's coming up next?

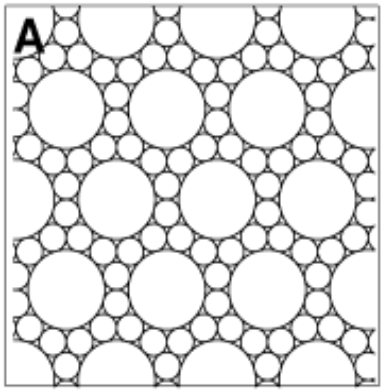
Packing to achieve efficiency



Specific Surface Area = 200,000 m^2 m^{-3}

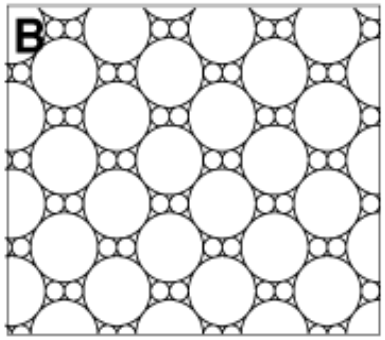


Searching for the optimized unit: A packing problem



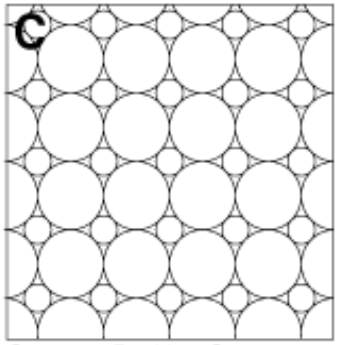
Compact Packing A

$R_{small} = 0.35 \times (R_{big})$



Compact Packing B

$R_{small} = 0.28 \times (R_{big})$



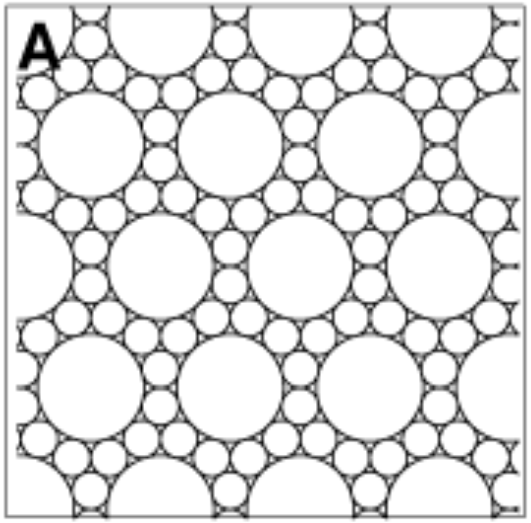
Compact Packing C

$R_{small} = 0.42 \times (R_{big})$

Mass Transfer Unit	Specific Surface Area $m^2 \cdot m^{-3}$
Wetted Wall	100-300
Hollow Membrane Contactor	~ 1500-3000
Our Previous Pattern	~ 2000-2800
Dense, Compact Pattern A	3549
Dense, Compact Pattern B	5180
Dense, Compact Pattern C	4601

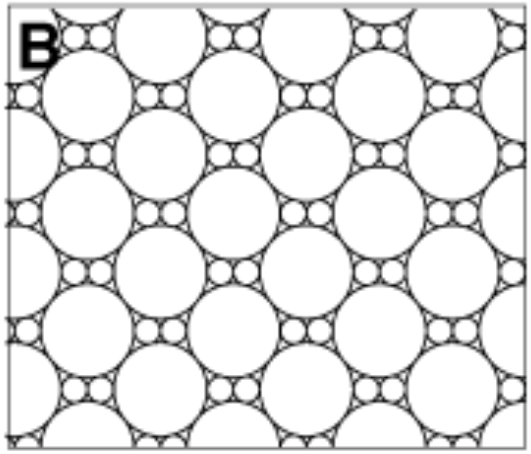
[math/0407145v2] Compact packing of the plane with two sizes of discs

Synthesizing Compact, Packed Geometry



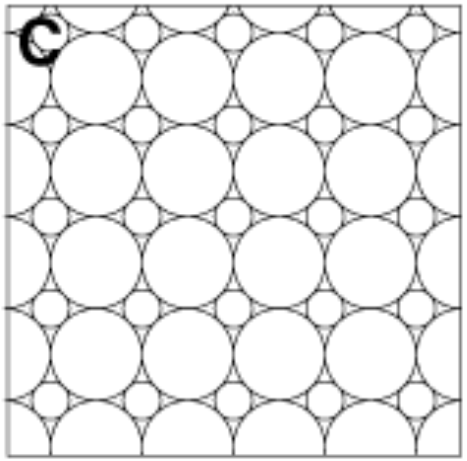
Compact Packing A

$R_{small} = 0.35 \times (R_{big})$



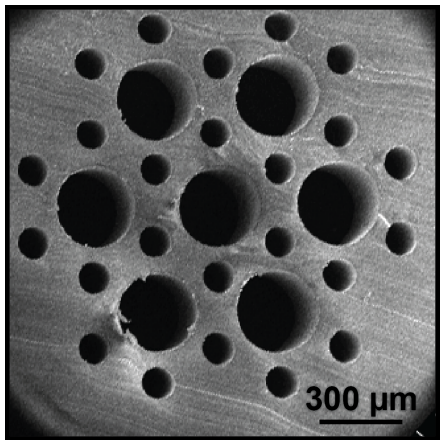
Compact Packing B

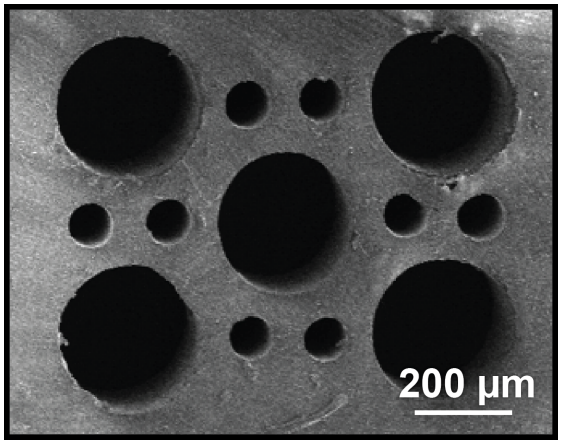
$R_{small} = 0.28 \times (R_{big})$

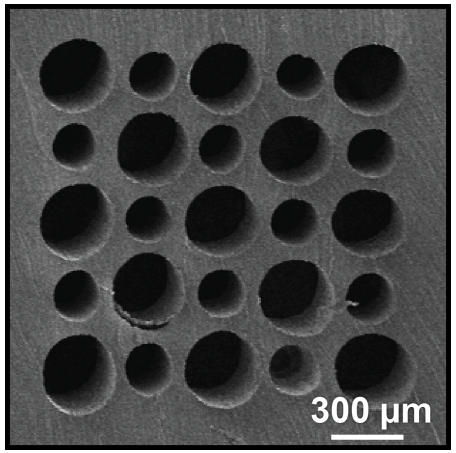


Compact Packing C

$R_{small} = 0.42 \times (R_{big})$

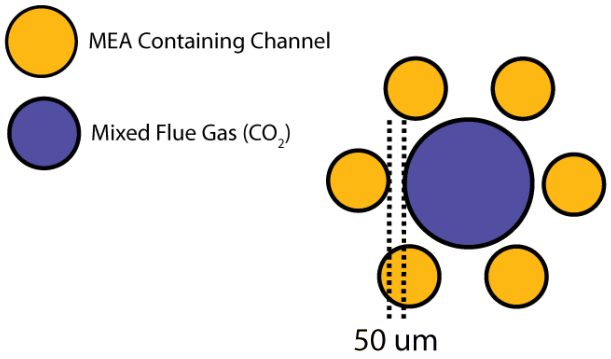


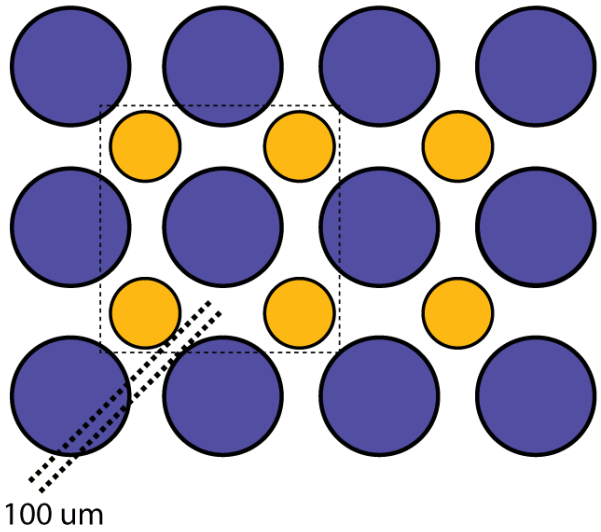




Full Set Coming 2013

Comparison of Channel Arrangements





Mass Transfer Rate

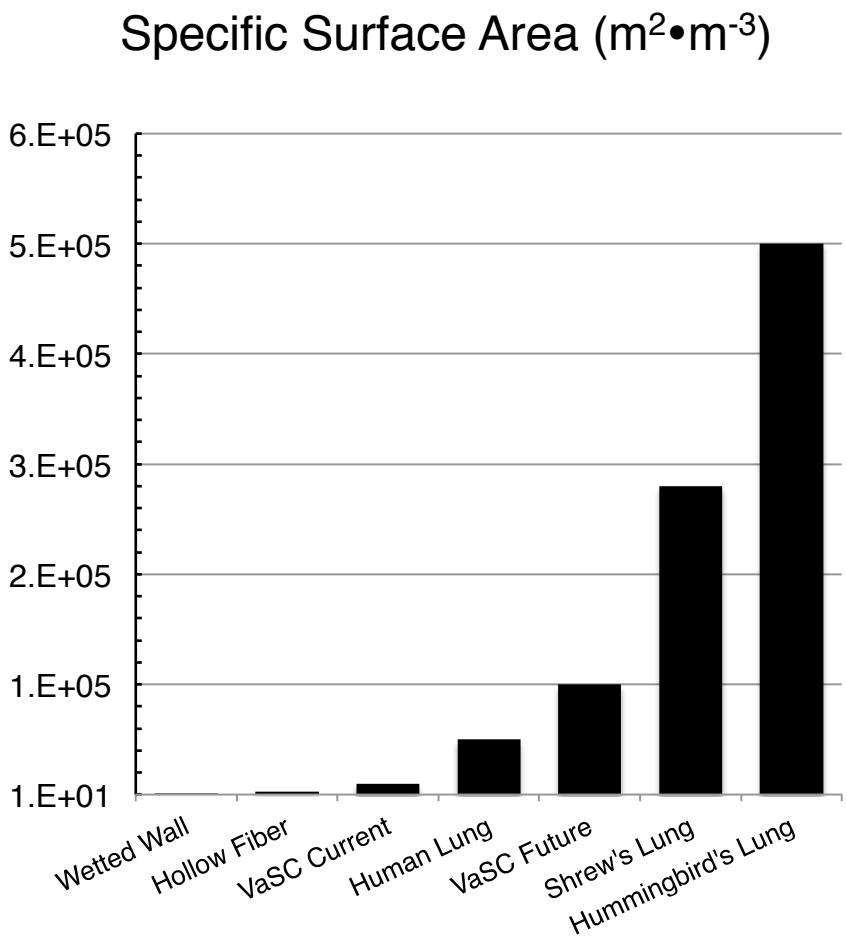
Pure CO_2

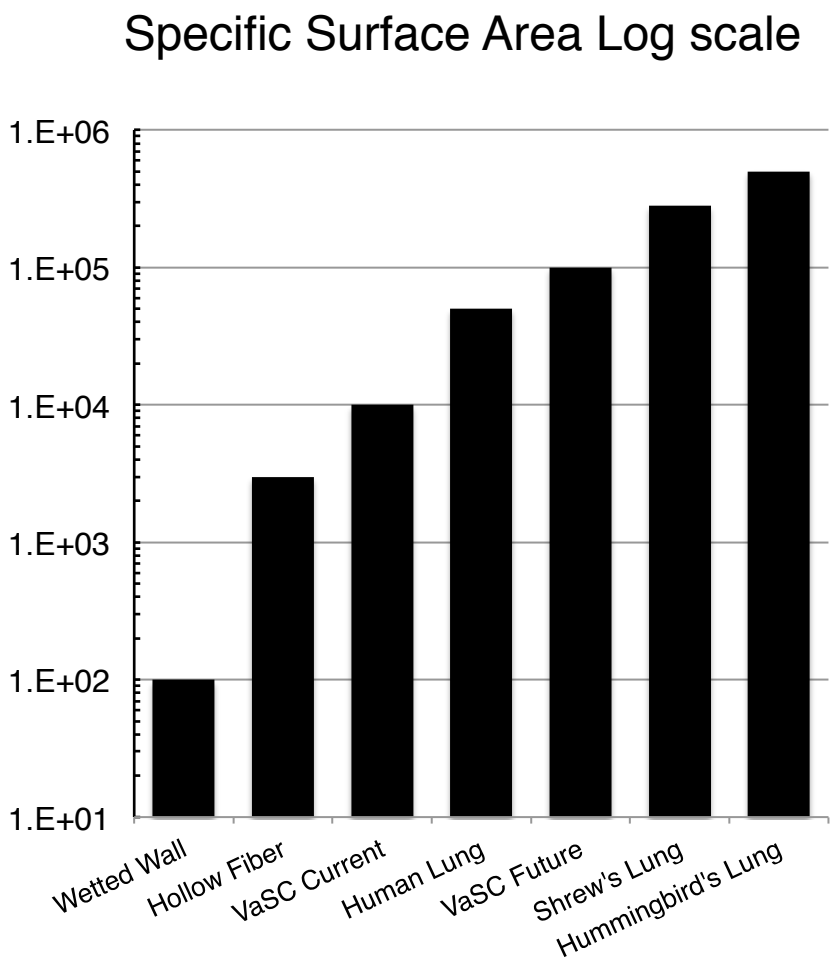
$$mol \cdot m^{-2} \cdot hr^{-1}$$

2.96 ± 0.35

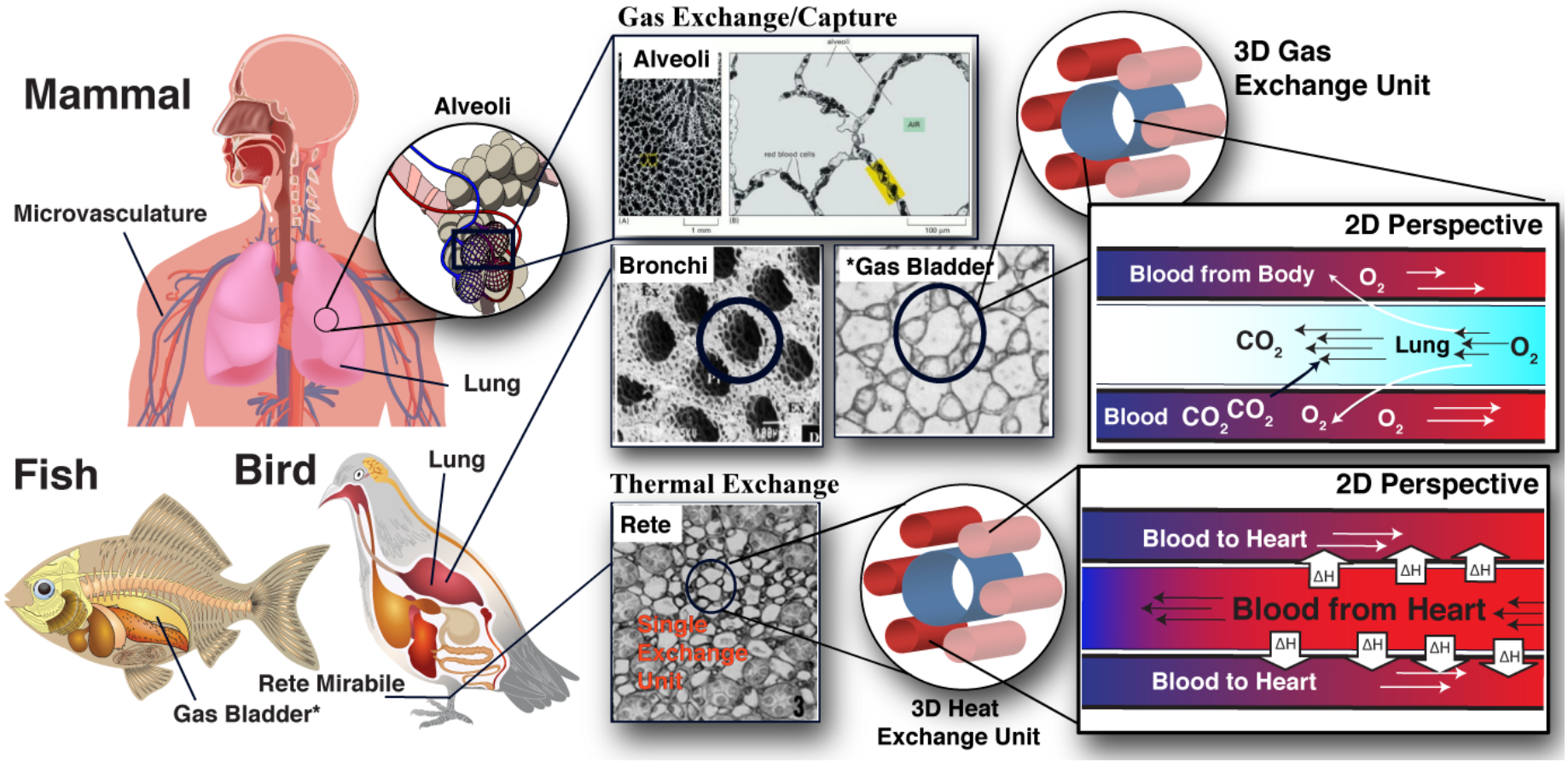
3.4 ± 0.25

Where does VaSC fit in?



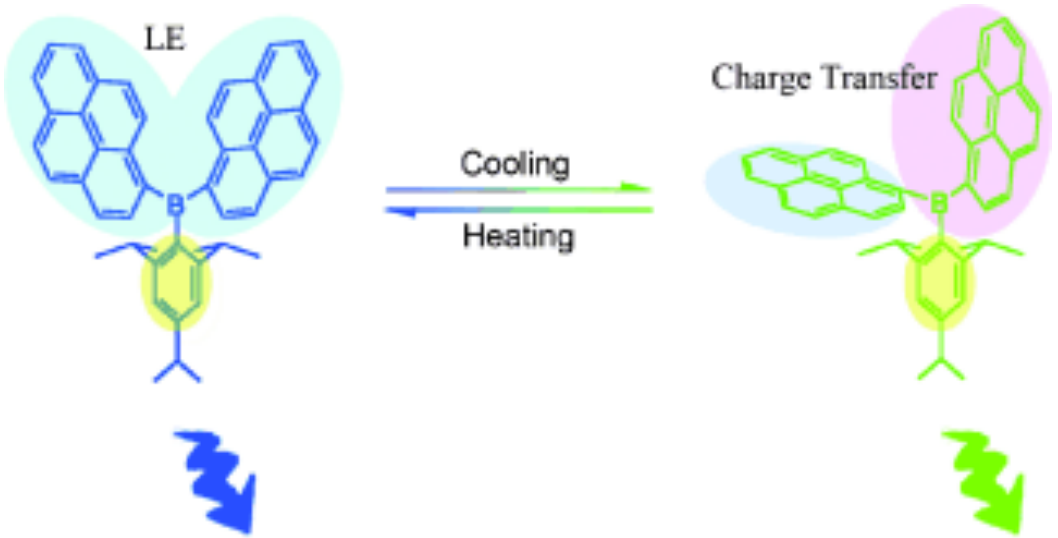


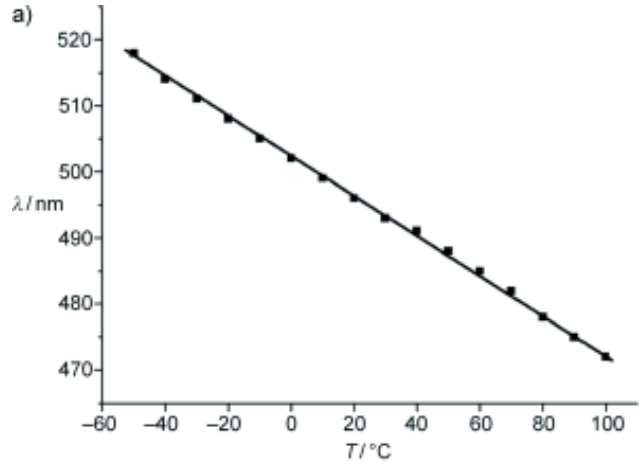
What about Heat Exchange?

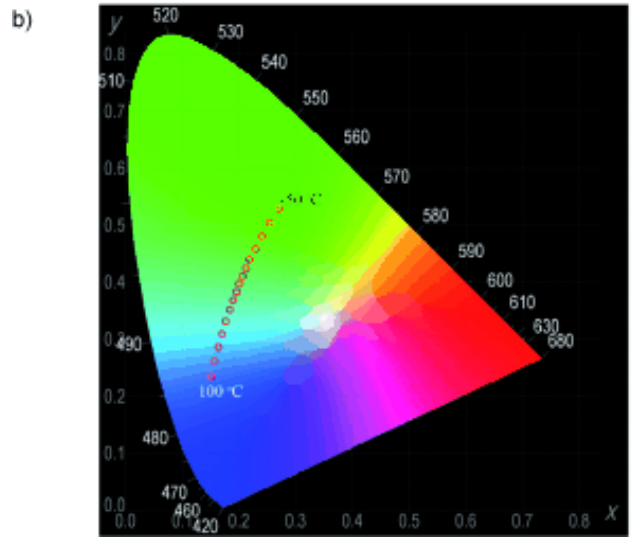


Thermal And Gas Exchange Are Based On Same Structures

A Fluorescent Thermometer

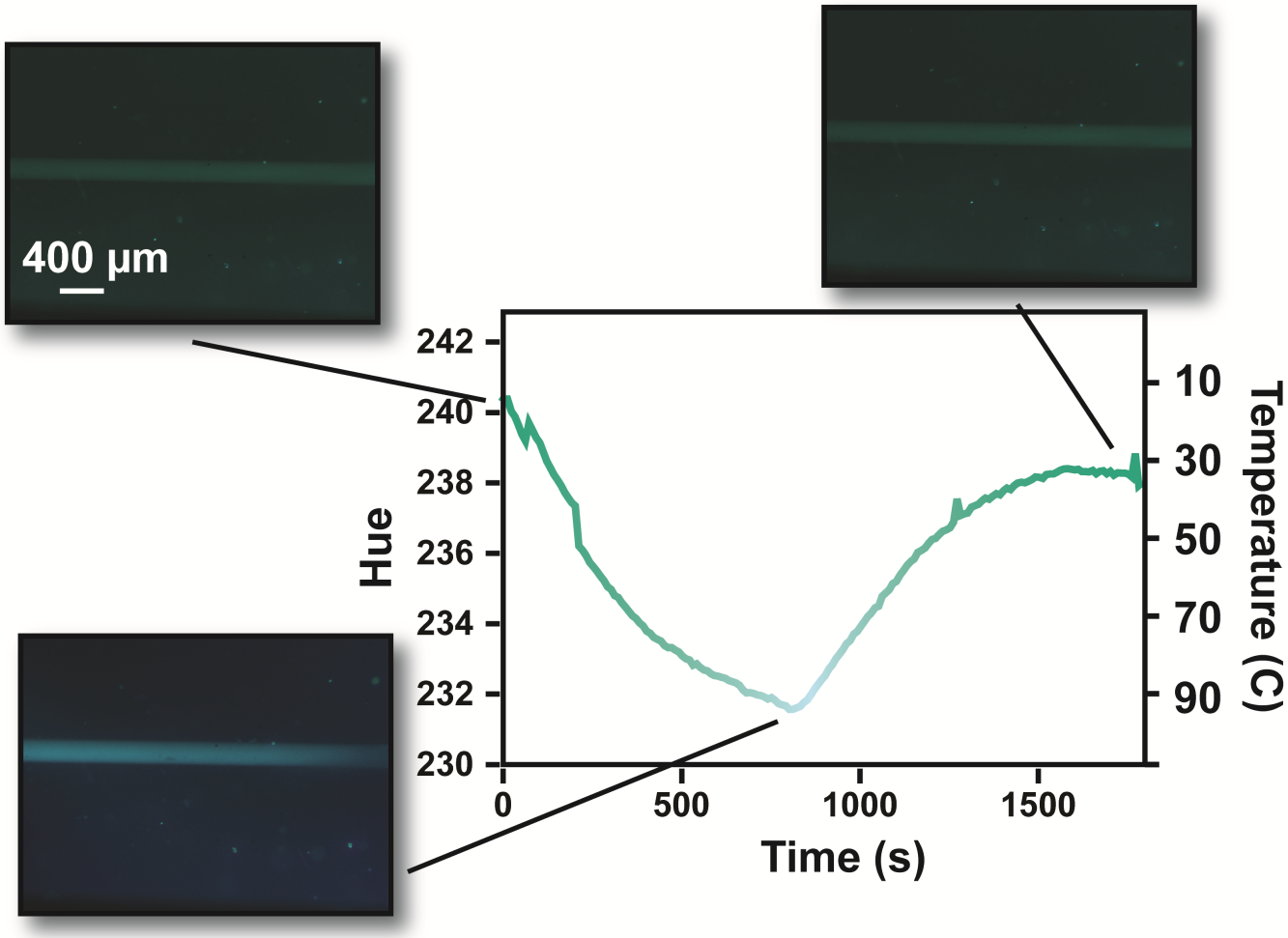






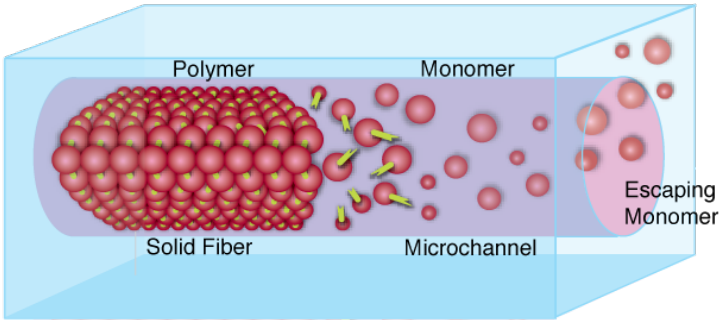
Feng, J. et al. ACIEE Edition 2011

Temperature in Micro-Vascular Material

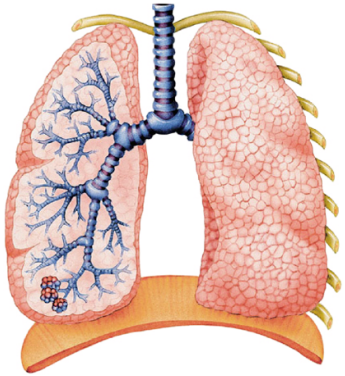


Micro-Vascular Exchange Units : Bio-Inspired Energy & Mass Transfer

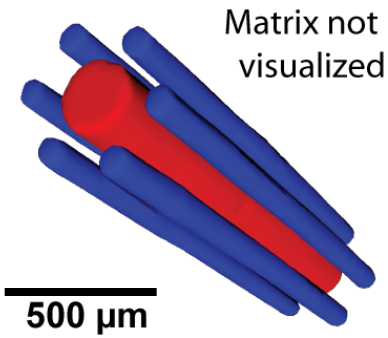
VaSC



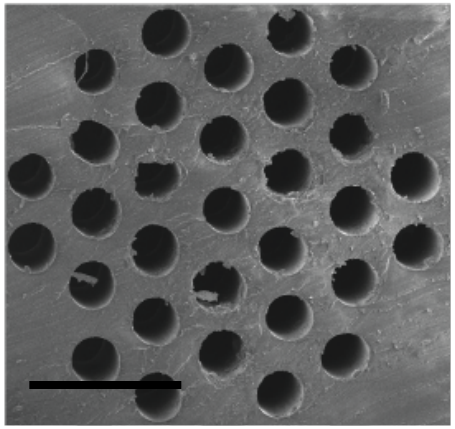
Our Motivation



Exchange Unit



Hierarchy



Next Year

- Heat Transfer
- Full Hierarchy

Acknowledgements

Jian-Guo Zheng and Wytze Van Der Veer & Calit2 Microscopy Center and Laser Spectroscopy Facility at the UCI. Sabra Djomehri at UCSF for assistance with μCT imaging. Hodge Harland, UCI Physical Sciences Machine Shop